NASA Contractor Report 163099

YF-12 COOPERATIVE AIRFRAME/PROPULSION CONTROL SYSTEM PROGRAM

VOLUME I

(NASA-CR-163099) YF-12 COOPERATIVE AIRFRAME/PROPULSION CONTROL SYSTEM PROGRAM, VOLUME 1 Final Report (Lockheed-California Co., Burbank.) 120 p HC A06/MF A01 CSCL 01C

N81-13044

Unclas

G3/05 29474

D. L. Anderson, G. F. Connolly, F. M. Mauro, and P. J. Reukauf

November 1980

JAN 81
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

NASA

NASA Contractor Report 163099

YF-12 COOPERATIVE AIRFRAME/PROPULSION CONTROL SYSTEM PROGRAM

VOLUME I

D. L. Anderson, G. F. Connolly, F. M. Mauro, and P. J. Reukauf
Lockheed-California Company
Burbank, California 91520

Prepared for
Dryden Flight Research Center

NASA
National Aeronautics and
Space Administration

1980

FOREWORD

This report has been prepared to document the results of the YF-12 Cooperative Airframe/Propulsion Control System (CAPCS) Program which was sponsored by NASA and accomplished by Lockheed Corporation (Advanced Development Projects). The report is provided in two volumes to segregate classified material and thereby facilitate wider use without the constraint of a "need to know." Volume I contains much of the descriptive technical material and is unclassified. Volume II contains the bulk of the detailed technical information in appendices and is classified.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of their colleagues in bringing the Cooperative Airframe/Propulsion Control System Program to completion. Unfortunately, we cannot name everyone who has assisted, but the following deserve special mention: Berwin Kock and Gene Matranga, NASA project managers, and Bill Fox, Lockheed project manager who advocated the program during its conception and managed it during the development phases.

During the system definition, development and flight test, the experience and efforts of Glen Gilyard, Jack Mayesh, Bill Fholer, Duane Dilzer, and George Volkenant, proved to be invaluable.

The contributions of the flight crews, Fitz Fulton, Don Mallick, Vic Horton and Ray Young are often overlooked when assessing the output of a program. Without their vast knowledge of how airplanes are supposed to fly and their judicious comments on the system operation during flight it would be impractical to develop new flight systems such as this.

The manuscript was skillfully edited by Ralph Marks to the extent that further involvement of the authors was minimized.

SUMMARY

The operational capability and efficiency of modern aircraft can be improved and flight crew workload can be reduced by integrating the airframe and propulsion control systems. To demonstrate the advantages afforded by this concept, the NASA Dryden Flight Research Center sponsored the Cooperative Airframe/Propulsion Control System (CAPCS) Program.

In February of 1975, Lockheed Corporation (Advanced Development Projects) was selected as prime contractor to perform Phase I of the CAPCS using a YF-12C high-performance aircraft. The YF-12C was selected because it exhibits a number of rapidly occurring interactions between the engine inlet and airframe control systems at speeds between Mach 2 and Mach 3. Since the program was directed toward civilian applications, aircraft ride qualities were also emphasized.

Several existing YF-12C analog control systems were converted to digital systems. Included were the air data computer, autopilot, inlet control system, and autothrottle systems. These systems were selected for conversion because they contained all the parameters of interest for integration and each had a suitable backup mode of operation, thereby assuring flight safety. The systems were digitally implemented because of the size and complexity of the controls integration problem. Digital control systems also provide the logic to handle the many variables and offer advantages in terms of speed, accuracy, and flexibility. The guiding philosophy called for Lockheed to reproduce the functions of the existing analog systems as closely as possible so that direct comparisons could be made to previous flight test data.

Primary development of the CAPCS was performed at the Lockheed Research Laboratory, Saugus, California (Rye Canyon facility). The existing airborne Univac 1816 Digital Computer Set was used to develop and integrate the software for the CAPCS program. Since the computer had only been previously qualified at MIL-E-5400, Class 1, special testing was performed

to ensure that problems would not be encountered when it was operated at 55,000 feet altitude and over MIL-E-5400, Class 2X, temperature ranges.

A large-scale mathematical simulation of the aircraft was used for integration testing and software checkout. The interface between the CAPCS and the simulation was made to represent the interface between the CAPCS and the aircraft as closely as possible. This resulted in a relatively problem-free installation when the CAPCS was installed on the aircraft.

Open loop frequency response tests were performed to determine optimum gain and phase responses for the digital transfer functions and to establish sampling rates. Gain tests were performed to evaluate the performance of the inlet scheduler module.

When satisfactory gain and phase responses were developed and sampling rates established, closed loop tests were performed to evaluate the CAPCS hardware and software. During closed loop tests, performance of the CAPCS and the analog systems were compared. Where the CAPCS was found to have poor performance, logic was altered and sample rates and gains were adjusted until satisfactory performance was achieved. The CAPCS was then installed in the YF-12C test aircraft.

Preflight tests were performed to verify the integrity of the CAPCS installation and to ensure that the CAPCS and all associated systems were operating correctly and compatibly. The installation checkout proved the CAPCS/aircraft wiring interface and verified that the CAPCS would respond satisfactorily to input signals. The interrelationships of the CAPCS and the associated aircraft systems were tested during preflight checkout using operational performance tests. Existing preflight procedures and the 90-day checkout procedures normally used to check performance of the analog counterparts to CAPCS formed the basis for the operational performance tests. These procedures were modified slightly to meet the specific requirements of the CAPCS installation and the CAPCS unique scaling requirements.

The general objective of the CAPCS Phase I flight tests was to demonstrate the operational feasibility of the digital system. This objective was accomplished. It was also hoped that the software could be brought up to production software standards in terms of storage and cycle time. This objective was not accomplished, however, due to the time limitations imposed by the foreshortened program.

Stated simply, the primary goal for the CAPCS flight test program was that the pilot should not be able to detect any difference in operation between the previous analog systems operation and the CAPCS over the full flight envelope of the aircraft. Understandably, this goal was quite subjective. However, the system worked as expected with some minor deviations which could have been corrected during a full development program.

A secondary goal of the flight test program was to assess the CAPCS reliability. During the flight test portion of the program only two problems of significance were discovered. The first problem was a region around 2.8 Mach number where many unstarts occurred when a standard duct pressure ratio schedule was used. The second problem was an incorrect representation of the automatic inlet restart function. This problem prohibited the inlet control system from accomplishing an automatic restart at some flight conditions. These problems could have been solved by changing the inlet control schedules and further developing the inlet restart logic based on flight test results. It is significant that in approximately 23 hours of flight there were no failures attributable to the digital system.

TABLE OF CONTENTS

VOLUME I

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS (Continued)

VOLUME II

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

VOLUME I

LIST OF ILLUSTRATIONS (Continued)

VOLUME II

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

VOLUME I

VOLUME II

LIST OF TABLES (Continued)

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/ Abbreviation	Definition
ADC	Air data computer
AFCS	Automatic flight control system
A/N	Automatic navigation
A/P	Autopilot
ATCS	Autothrottle control system
$A_{TS(X)}$	Summation variable
A_{TWO}	Washout output
$A_{V(X)}$	Altitude hold variable
CONIN	Control input
DEAP1	Pitch autopilot input to SAS - degrees
DEAP2	Trim actuator output
D_I	Inlet drag - lb
D_{PIN}	DEAP1 input - degrees
DPR	Duct pressure ratio
FN	Gross thrust - lb_f
G_{LIM}	G limiter schedule
GS(X)	Gain switch setting
H	Altitude - ft
H_{DS}	Summation variable - deg/sec
H_G	Lateral axis heading gain
H_{INT}	Integrator output - degrees
KEAS	Knots equivalent airspeed
KIAS	Knots indicated airspeed
K_S	Equivalent velocity - knots
$K_{V(X)}$	KEAS hold variable

PRECE' ,NG PAGE BLANK NOT FILMED

Symbol/ Abbreviation	Definition
L_{AT}	Left actuator input
L_{FB}	Left actuator feedback
L_{NCH}	Notch line output
L_{OUT}	Altitude output
L_{SR}	Steering command
L_{V3}	Heading variable
L_{V4}	Steering input
L_{V6}	Limiter input
L_{V7}	Limiter output
M	Mach number
M_{CL}	Uncorrected free stream Mach number
M_{TVI}	Lag output - degrees
$M_{V(X)}$	Mach hold variable in deg/sec
N_Y	Lateral acceleration
N_Z	Normal acceleration
$\dot{p}$	Pressure rate of change
P_{AG}	Pitch attitude aerodynamic gain
PAP2	Integrator input - deg/sec
PAP3	Integrator output - degrees
PAP4	Limited output - degrees
PAP6	Attitude variable - degrees
PAP7	Attitude variable - degrees
PAP8	Fader - degrees
PAP9	Lag output - degrees
PAP10	Hysteresis output

Symbol/ Abbreviation	Definition
PLA	Power lever angle
P_{MG}	Mach rate gain
P_o	Standard pressure
P_{LM}	Total pressure measured on inlet external cowl
P_s	Nose boom static pressure - lb/ft^2
P_sD8	Static pressure on outer surface of cowl
P_{SM}	Summation variable - degrees
P_{STAT}	Static pressure
P_t	Nose boom total pressure - lb/ft^2
PT_2	Compressor face total pressure - lb/ft^2
P_{TOT}	Total pressure
P_{TRM}	Trim actuator input
q	Pitch rate - deg/sec
Q_{BD7}	Notch output - degrees
q_c	Dynamic pressure - lb/ft^2 (differential pitot-static pressure)
Q_G	Pitch gyro input
r	Yaw rate - deg/sec
R_{AT}	Right actuator input
R_{FB}	Right actuator feedback
R_{HO}	Right hysteresis output
R_{LG}	Lag output
R_{NH}	Notch output
R_s	Normalized pressure
R_{SAS}	Autopilot input to SAS
SAS	Stability augmentation system

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

Symbol/ Abbreviation	Definition
T_{HL}	Lag output
T_{HLI}	Lag input
T_{MON}	Tracking monitor output
T_{RE}	Right engine trim
V_{TOT}	True airspeed
T_{V4}	Attitude variable
V_e	Equivalent velocity - ft/sec
W_f	Engine fuel flow - lb/sec
W_{ec}	Engine corrected airflow - lb/sec
W_{ic}	Inlet corrected airflow - lb/sec
$X_{K(gain)}$	Pitch autopilot gain setting
X_{SP}	Spike position - IN
YD	Forward bypass door position - IN
α	Angle of attack - degrees
α_o	Uncorrected angle of attack - degrees
β	Angle of sideslip
$\Delta \ln P_s$	Differential log P_s
$\Delta \ln$ RMI	Differential log q_c
$\Delta \ln V_c$	Differential log KEAS
ΔP_α	Angle of attack differential pressure - lb/ft^2
ΔP_β	Angle of sideslip differential pressure - lb/ft^2
ζ_a	Aileron position - degrees
ζ_e	Elevator position - degrees
ζ_v	Rudder position - degrees
γ_c	Mach trim schedule

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

Symbol/ Abbreviation	Definition
θ	Pitch attitude
θ_H	Pitch altitude position gain
θ_{INS}	Pitch attitude
$\theta_{\int H}$	Pitch integrated gain
θ_Σ	Pitch attitude sum (pitch attitude plus trim wheel setting)
ΔKEAS	KEAS input
ΔM	Mach input
ΔM_T	Mach trim error - degrees
$\Delta\theta$	Pitch attitude input
Λ_ϕ	Attitude error - degrees
Δ_ψ	Heading error
τ	Lag time constant
τ_{THL}	Pitch attitude lag time constant
ϕ_Σ	Roll attitude sum
ϕ_{BK}	Bank angle
ϕ	Roll attitude - degrees
$\dot{\phi}$	Roll rate - deg/sec
ψ	Heading - degrees

Figure 1-1. YF-12C Aircraft

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION 1
INTRODUCTION

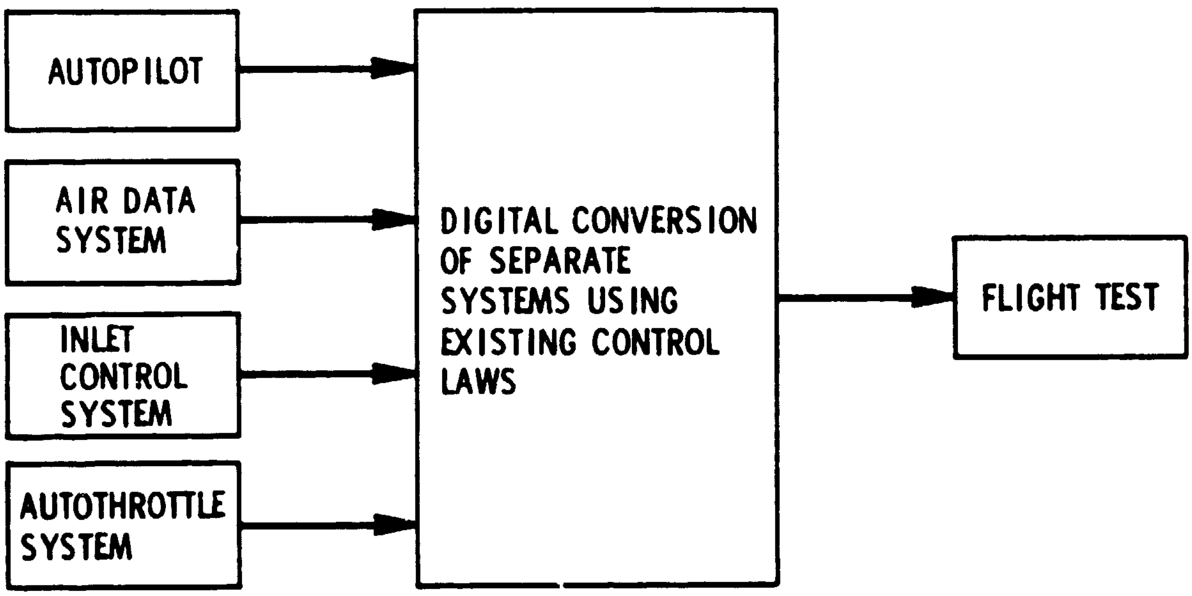
The operational capability and efficiency of modern aircraft can be improved by use of integrated airframe/propulsion control systems. The integration of control systems allows the minimization of undesirable interactions and the maximization of desirable interactions between the various aircraft components. Flight crew workload is also reduced by greater automation, allowing more time for operation of systems not directly involved with controlling the aircraft.

Historically, very little integration of systems has been accomplished for several reasons. One reason is that in older generation aircraft the number of systems was small, the interactions were fewer and the pilot workload was smaller. For such aircraft the pilot could effectively integrate the systems by his control inputs. Another reason is that it was desirable from a design viewpoint to have independent systems so that each system could be analyzed separately. With this approach designers could confidently expect the total system to operate efficiently in the manner intended. Unfortunately, however, today's sophisticated aircraft have a multitude of controlled, rapidly interacting variables and it is difficult to predict what the component interactions will be. Moreover, the pilot can not be expected to react rapidly enough to be effective in controlling the interactions. Thus, it is imperative that future aircraft control systems be constructed with a maximum of integration and flexibility so as to afford maximum utility and efficiency for every foreseeable mission.

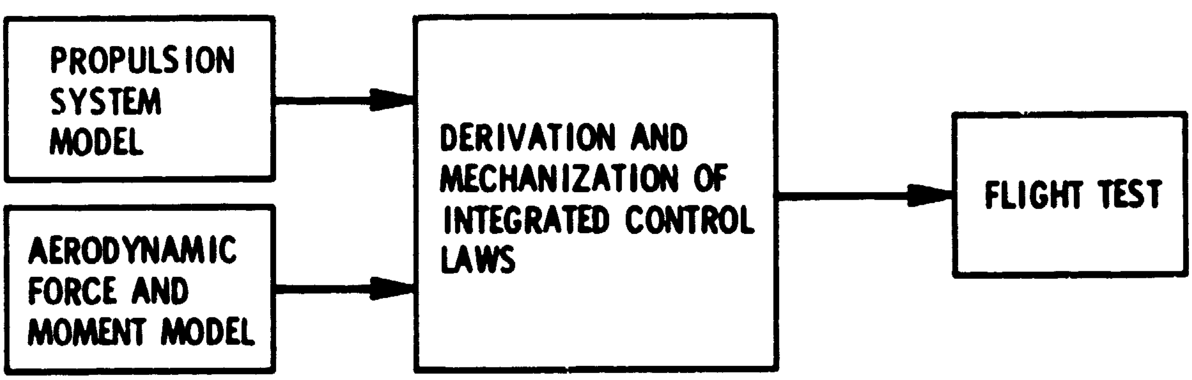
The NASA Dryden Flight Research Center sponsored the Cooperative Airframe/Propulsion Control System (CAPCS) Program to demonstrate the advantages of such control systems. The YF-12C aircraft (Figure 1-1) was selected because it exhibits a number of rapidly occurring interactions between the inlet and airframe control systems at speeds between Mach 2 and Mach 3. The goals of the program were to show increased efficiency and better flight path control across the flight envelope of the aircraft. This work was directed toward civilian applications so aircraft ride qualities were also emphasized.

The CAPCS program, as conceived, encompassed two developmental phases (Ref. 1). In the first phase (Figure 1-2) the existing YF-12 analog air data computer, autopilot, inlet control system and autothrottle system were to be converted to digital systems. These particular systems were selected because they contained all of the parameters of interest for integration and each had a suitable backup mode of operation, thereby assuring flight safety. Digital implementation of the CAPCS was considered necessary because of the size and complexity of the controls integration problem. Digital control systems provide the logic to handle the many variables and offer advantages in terms of speed, accuracy and flexibility. In the second phase of the program optimal control laws were to be developed and mechanized on the digital system. Unfortunately, however, only the phase I objectives were attained because the CAPCS program was terminated before phase II was initiated. Thus, only the phase I objectives (conversion of the various analog systems to digital systems) are addressed in this report.

In February of 1975, Lockheed Corporation (Advanced Development Projects) was selected as prime contractor for the CAPCS phase I effort. Lockheed's responsibilities included system definition, selection of hardware and production of the associated software. The guiding philosophy called for Lockheed to reproduce the functions of the existing analog systems as closely as possible so that direct comparisons could be made to previous flight test data. Two exceptions to this philosophy were made: In the area of air data computations the equations were applied in such a manner as to fully utilize the capabilities of the digital computer; and two new control features were added to the pitch autopilot: namely, speed hold and altitude hold operating



(A) ANALOG TO DIGITAL CONVERSION PHASE



(B) INTEGRATED CONTROL LAW PHASE

Figure 1-2. CAPCS Program Developmental Phases modes. The new equations for these modes were supplied by NASA.

The primary development of the CAPCS took place at the Lockheed Research Laboratory, Saugus, California (Rye Canyon facility) (Figure 1-3). Here the system was tested by interfacing it with a simulation of the YF-12 aircraft, thus allowing the hardware and software to be checked out in a closed loop. Considerable emphasis was given to making the interfaces between the CAPCS and the aircraft simulation as realistic as possible. After testing was complete, the system was installed in a YF-12C, serial no. 937, and during the May - September 1977 period, 10 missions were flown at NASA Dryden Flight Research Center which demonstrated the system over the full flight envelope of the aircraft. After that, three additional missions were flown by the USAF for pilot evaluation purposes.

This report has been prepared to document the technical aspects of the YF-12 CAPCS program. The report has been prepared in two volumes to facilitate use and consists of a Summary, five sections and ten appendices. The highlights, results and general background information are presented in the Summary for the benefit of the casual reader. For those who may not be familiar with the program, the CAPCS is described in Section 2 and some of the basic design considerations are also presented. Section 3 contains a technical account of the CAPCS hardware and software development. CAPCS laboratory and flight test methods and results are described in Section 4. Program results and conclusions are summarized in Section 5. The bulk of the technical material is provided in Appendices A thru J in Volume II. A List of Symbols and Abbreviations is also provided in order to define the various symbols, abbreviations and acronyms used in this report. Documents referred to herein are identified under References at the end of Volume I.

Figure 1-?. Computer Facility at Lockheed Rye Canyon Research Laboratory

ORIGINAL PAGE IS
OF POOR QUALITY

SECTION 2
SYSTEM DESCRIPTION

2.1 GENERAL DESCRIPTION

The Cooperative Airframe/Propulsion Control System (CAPCS) is a digital control system that was developed on an experimental basis to demonstrate the feasibility of replacing the analog air data system, the analog autopilots, the analog automatic inlet control system and the analog autothrottle system on the YF-12C aircraft with a digital computer that is capable of performing the same functions as its analog counterparts. Figure 2-1 shows the relationship of the CAPCS digital computer and the associated onboard equipments. Physically, the CAPCS consists of a general purpose digital computer, an interface unit, a control unit, a display unit and four pressure transducers. These units are interconnected in the manner shown in Figure 2-2 and are described in the following subparagraphs.

2.1.1 CAPCS Digital Computer

A Univac Model 1816 Digital Computer set, an available "off-the-shelf" unit, was selected for this application. Communication to and from the computer is performed over two types of interfaces: an input/output port and a multiport memory interface.

The computer is configured with four input/output (I/O) channels. In the airborne configuration two of the I/O channels are used: one for the control unit and the other for the interface unit. During ground operation the remaining two I/O channels are used for ground support equipment (see Figure 2-2). The I/O channels are 16-bit parallel channels that operate in a full duplex mode. The full duplex mode allows for simultaneous input and output transfer operation. Each input channel and each output channel has its own set of parallel data lines and control lines. Output channels are used to transmit data and external functions (or commands) to peripheral equipment.

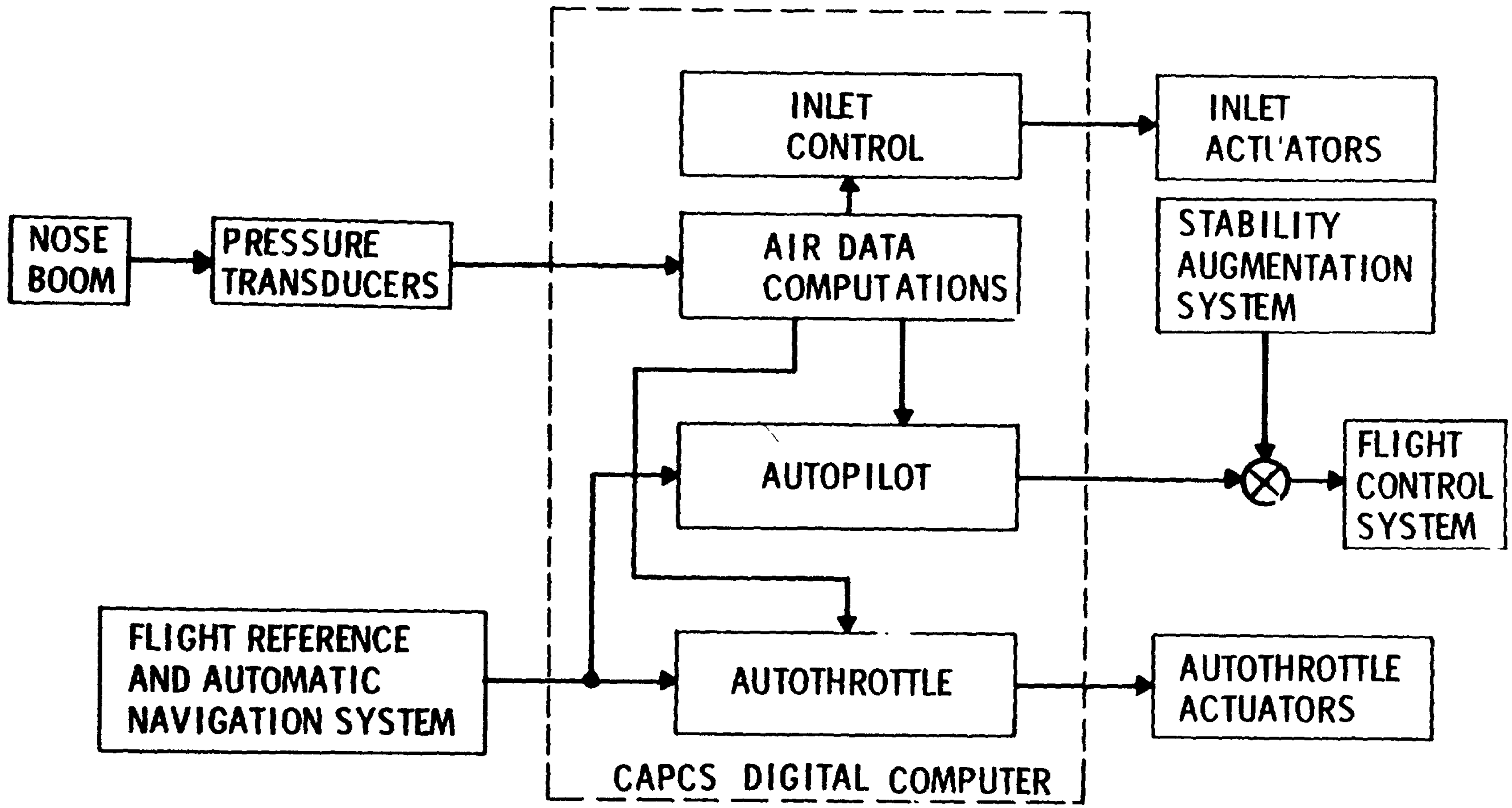


Figure 2-1. CAPCS Digital Complete and Associated Airborne Systems

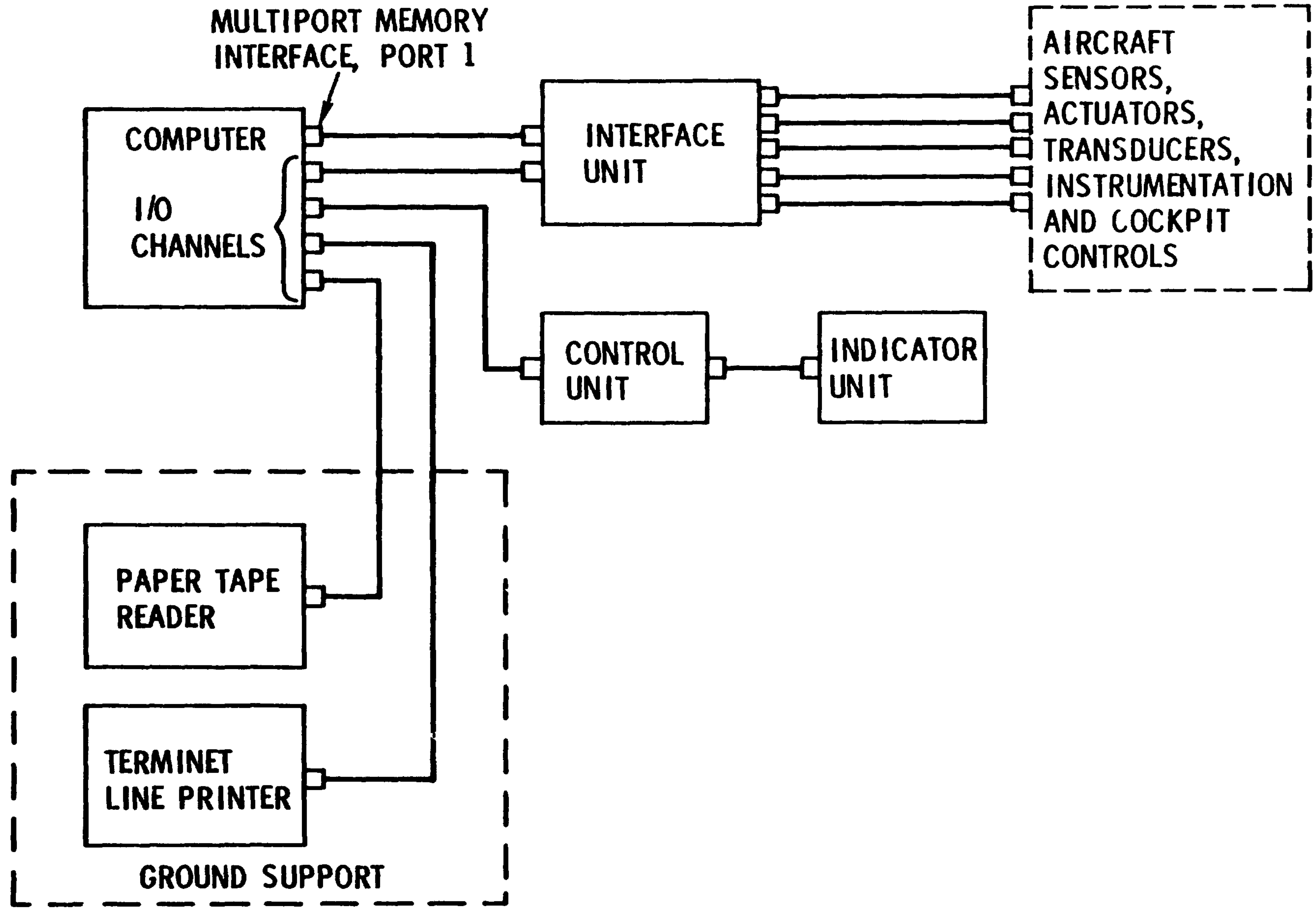


Figure 2-2. CAPCS Interconnection Block Diagram

Input channels are used to receive interrupt codes or data from the same equipment. All input/output activity is asynchronous and the timing is dependent on the speed of the peripheral. The multiport memory interface, port 1, allows connection of an external memory bank to augment the two 16k word banks within the computer.

As indicated in Figure 2-1, the CAPCS computer receives inputs from pressure transducers and in turn performs air data computations. It then utilizes the latter, along with inputs from the associated flight reference and automatic navigation systems, to generate autopilot, throttle and inlet control commands.

2.1.1.1 Air Data Computations. Air data computations are performed by the CAPCS computer using total and static pressure inputs from the aircraft noseboom and associated pressure transducers (Figure 2-3). The noseboom features a compensated pitot-static probe and an offset hemispherical head flow direction sensor. The pitot-static probe senses impact pressure (P_t) at the probe tip and static pressure (P_s) at two sets of orifices. Flow angularity in the pitch plane (angle of attack) is determined by the magnitude of the pressure difference (ΔP_α) between two orifices in the vertical plane of the hemispherical head. Similarly, flow angularity in the yaw plane (sideslip) is determined by the magnitude of the pressure difference (ΔP_β) between two orifices in the horizontal plane of the hemispherical head. Pressures P_t, P_s, ΔP_α and ΔP_β are measured by four high-accuracy pressure transducers. The outputs from the pressure transducers are processed by the digital computer, which computes the following outputs: true airspeed, pressure altitude, Mach number, knots equivalent airspeed (KEAS), angle of attack, angle of sideslip, Mach number, altitude rates of change, and logarithmic representations of static pressure and compressible dynamic pressure; it also computes differences between Mach number and a Mach number schedule (Mach error), KEAS and KEAS schedule (KEAS error), and a KEAS bleed schedule as a function of Mach number.

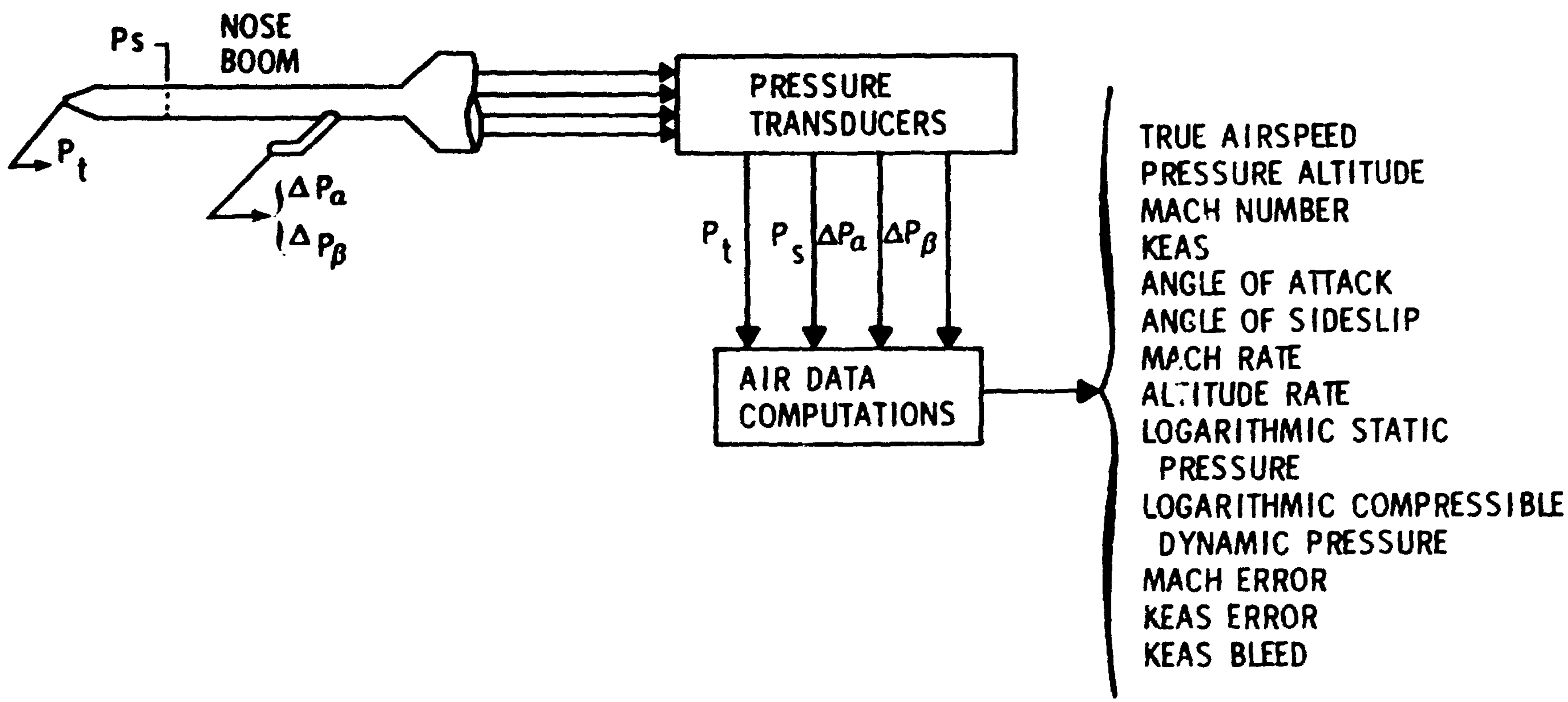


Figure 2-3. CAPCS Air Data Computation Input/Outputs

2.1.1.2 Autopilot. The autopilot provides a way to achieve hold modes in the roll and pitch axis during flight. Use of the autopilot is optional and often depends upon mission requirements. The autopilot is comprised of roll and pitch autopilots which use the above air data computations as well as inputs from the automatic navigation system and the flight reference system to maintain its modes of operation. The autopilot outputs are summed with stability augmentation system (SAS) outputs and applied to the flight control surface actuators.

The roll autopilot (Figure 2-4) provides three modes of control: attitude hold, heading hold, and automatic navigation. In the attitude hold mode, a roll rate gyro input and an attitude hold reference signal from the flight reference system are used. In the automatic navigation mode, automatic navigation system outputs are used. In the heading hold mode, outputs from the flight reference system are used. Roll autopilot outputs are combined with roll SAS outputs and the resulting signals are supplied to the elevon actuators.

The pitch autopilot provides five modes of control: attitude hold, Mach hold, KEAS hold, altitude hold and Mach trim. An automatic trim function is provided during all of these modes. A block diagram showing inputs to the pitch autopilot is shown in Figure 2-5. The attitude hold mode uses the pitch attitude reference, logarithmic static pressure and pitch rate gyro inputs. A pitch wheel in the cockpit allows the pilot to make minor corrections to the reference attitude. The Mach hold mode uses internally generated signals of Mach number error and Mach number rate of change. The KEAS hold mode is similar to the Mach hold mode except that KEAS rate of change and KEAS error inputs are used. The KEAS hold mode is capable of maintaining a specified KEAS bleed line. The altitude hold mode uses internally generated signals of altitude and altitude rate of change to keep pressure altitude constant. The pitch axis autopilot outputs are combined with the pitch SAS outputs and fed to the elevon actuators.

The Mach number trim system provides artifical speed

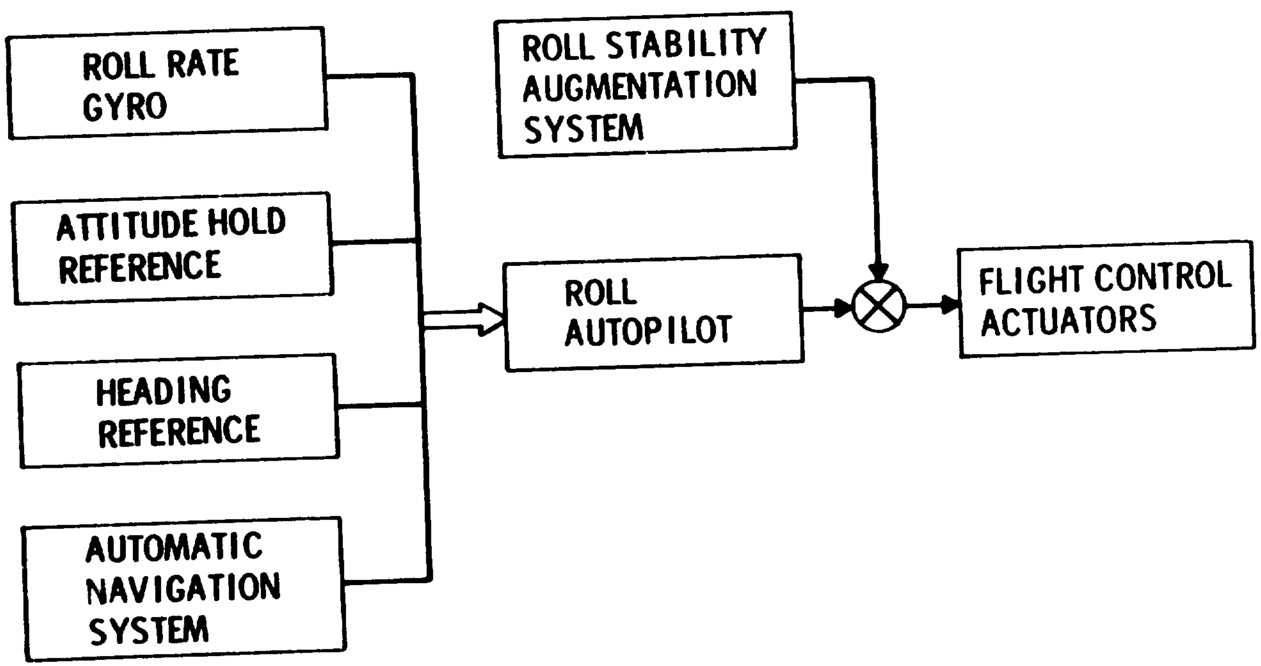


Figure 2-4. Roll Autopilot Inputs

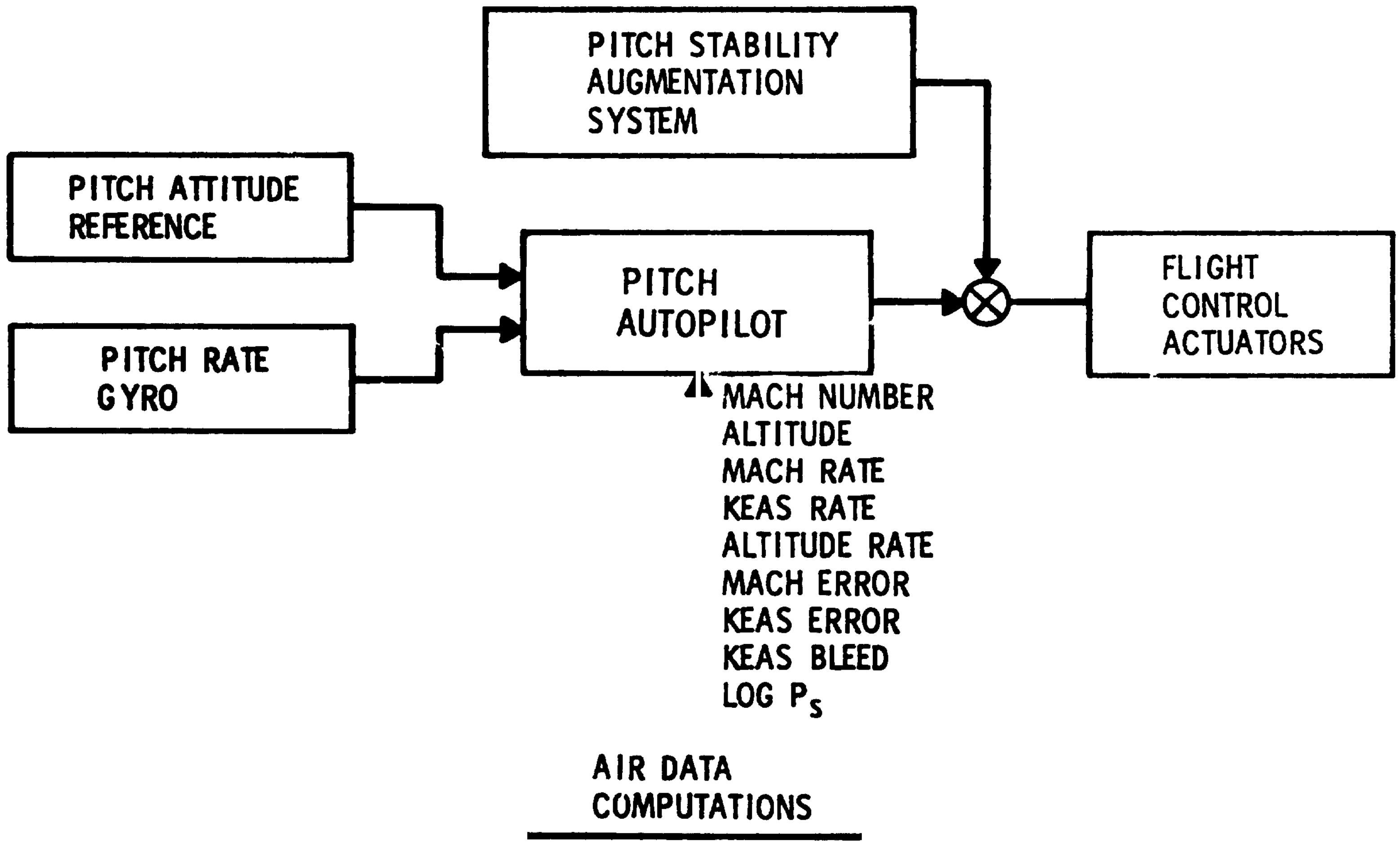


Figure 2-5. Pitch Autopilot Inputs

stability during aircraft accelerations or decelerations in the Mach number range from 0.2 to 1.5 whenever the pitch autopilot is disengaged. The system uses internally generated Mach number inputs which, after processing, are fed to the pitch trim actuator.

2.1.1.3 Autothrottle. The autothrottle has two control modes: Mach number hold and KEAS hold. The purpose of the autothrottle is to allow these operational modes without changing the longitudinal flight path of the airplane. Mach number error and KEAS error are input to the autothrottle subsystem from the air data computations section and pitch attitude is input from the flight reference system (see Figure 2-6). The digital computer processes these inputs and produces a command signal which goes to the autothrottle servos. Both engines are controlled symmetrically in the afterburning range.

2.1.1.4 Automatic Inlet Control. The inlet (Figure 2-7) is of the translating spike type, with approximately 40 percent of the compression occurring externally and 60 percent internally. Boundary layer air is removed through a slotted surface on the spike and a ram scoop or shock trap on the cowl. Forward bypass doors of the rotary type are used to match engine airflow to inlet airflow and to control the position of the terminal shock wave. Aft bypass doors just in front of the compressor face provide additional bypass capability for intermediate Mach numbers. Aft bypass airflow and shock trap bleed air are ducted rearwards to the ejector of the J58 engine. Spike bleed and forward bypass flow are dumped overboard through louvered exits.

The CAPCS computer achieves automatic inlet control by generating Spike Position and Duct Pressure Ratio commands for each inlet. In doing so it processes data inputs from a normal acceleration transducer near the aircraft center of gravity as well as angle of attack, angle of sideslip, and Mach number data inputs (see Figure 2-8).

The spike position loop is used to control the throat area and the contraction ratio of the inlets. The spike position schedule is primarily a

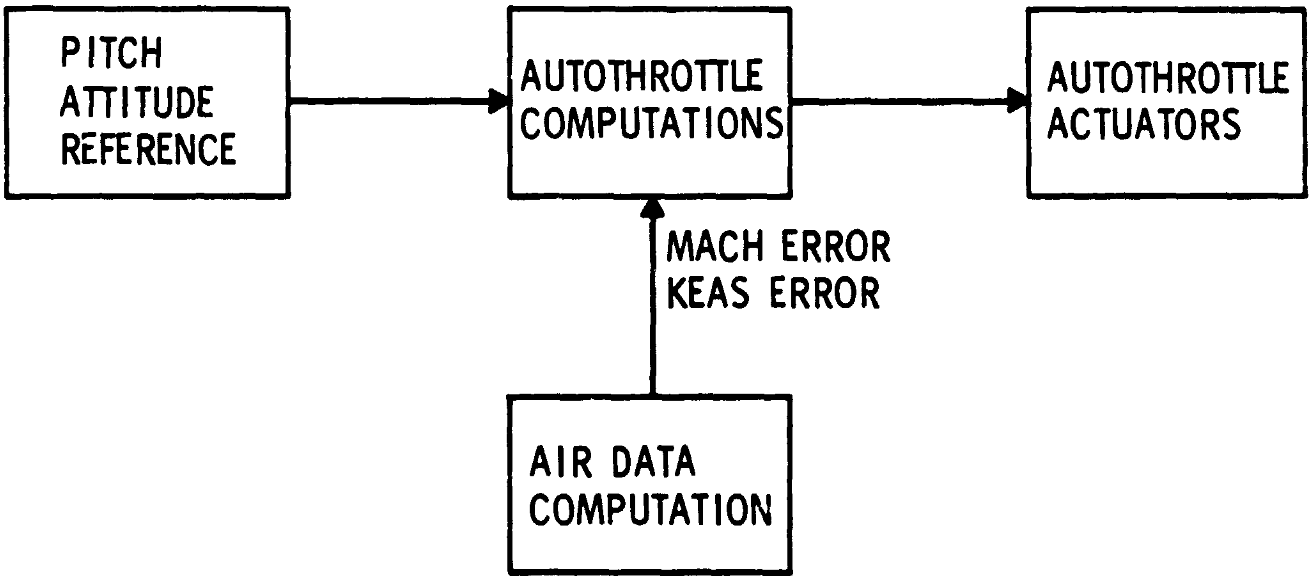


Figure 2-6. Autothrottle Inputs

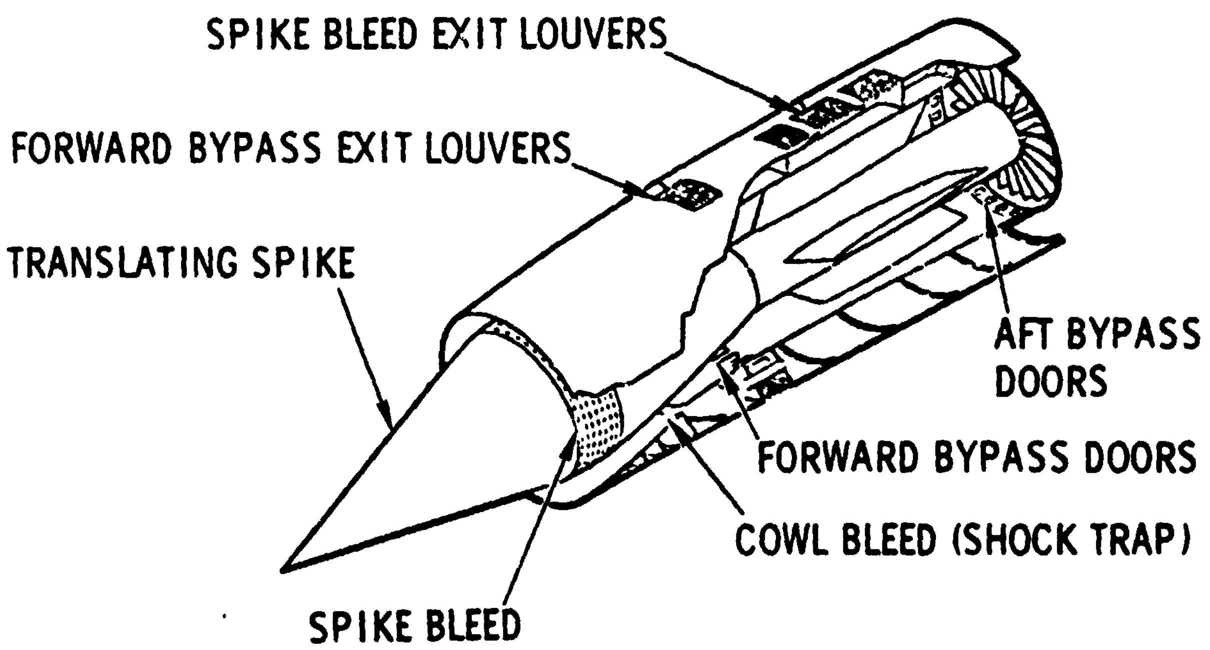


Figure 2-7. Inlet Physical Components

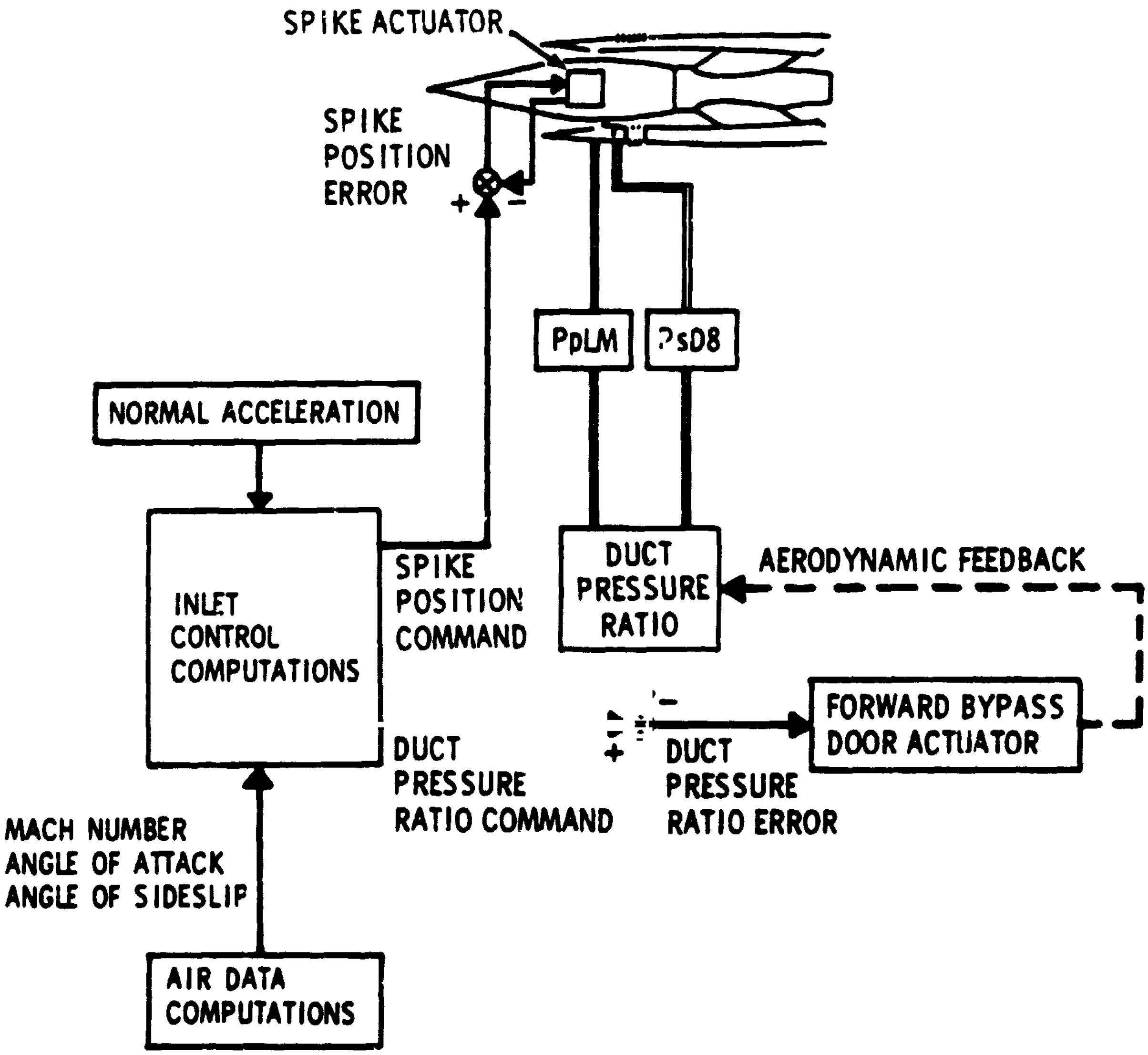


Figure 2-8. Automatic Inlet Control Functional Block Diagram

function of freestream Mach number. The nominal spike schedule is biased to more forward positions when deviations from nominal values of angle of attack, angle of sideslip or normal acceleration occur.

The duct pressure ratio loop is used to control the position of the terminal shock wave in the inlet. The duct pressure ratio is the ratio of a static pressure in the inlet throat, PsD8, to an impact pressure on the outer surface of the cowl, PpLM. The throat static pressure varies as a function of the terminal shock wave position. The forward bypass doors are used to move the terminal shock wave until the duct pressure ratio measured by the system matches the duct pressure ratio commanded by the inlet computer. There is a nominal duct pressure ratio schedule which varies with airplane Mach number. This schedule was derived from wind tunnel and flight tests and is intended to result in the desired shock position. The schedule is biased to a lower duct pressure ratio for deviations from nominal values of angle of attack, angle of sideslip, and normal acceleration. At a given flight condition, this lower duct pressure ratio command increases the opening of the forward bypass doors and moves the terminal shock wave farther downstream.

An inlet unstart sensor is used to determine when the normal shock moves outside the inlet. When an unstart occurs, the unstarted inlet is switched to an open loop restart mode. The forward bypass doors open at maximum rate to the full open position, and the spike moves 15 inches forward or full forward if it is retracted less than 15 inches. The spike then returns slowly to the scheduled position and the bypass doors slowly close to return the duct pressure ratio to the scheduled command.

The airplane rolling and yawing motions associated with an inlet unstart can be severe. To reduce the severity of the unstart transient, the opposite inlet switches automatically into the restart mode at the same time as the affected inlet. This mode, which is called a crosstie, is so effective that sometimes the pilot cannot tell which inlet unstarted.

2.1.2 Manual Inlet Control

For flight safety reasons a manual inlet control capability is provided which is independent of the automatic inlet control system. When using the manual system the pilot observes the cockpit display of Mach number and positions the spike and bypass doors of each inlet accordingly.

2.1.3 Interface Unit

The interface unit was supplied by Minneapolis-Honeywell and built to Lockheed-ADP specifications. It converts or formats the analog or digital input signals from the associated aircraft systems to a form compatible with the Univac 1816 Digital Computer and converts or formats the computer output signals to a form suitable for input to the same aircraft systems. Communications to and from the computer are maintained over two types of interfaces: the input/output port and a multiport memory interface.

The interface unit was designed around the multiport memory interface. The interface unit acts like a CPU memory and runs asynchronously. Every 2.5 milliseconds the interface unit converts and formats all analog signals (synchro, AC and DC) and stores the results in a semiconductor RAM. The computer accesses a particular converted parameter by loading a register from the respective address in the RAM. Parameters are output from the computer in a similar manner. The process of converting digital parameters to an analog form is RAM. The memory addresses assigned to the various I/O functions are listed in Appendix G.

The serial PCM data is transmitted via the I/O port in the interface unit. The block of PCM data to be transmitted is organized within the computer memory. The blocks are 220 16-bit words in length with the first two words being the sync pattern. Each word is transmitted to a double buffer arrangement in the interface unit. When a word is converted from parallel to serial, the next word is loaded into the output buffer and the computer is requested to send a word to the holding buffer.

2.1.4 Control and Indicator Units

Separate control and indicator units were designed and built by NASA DFRC to provide control and indicator display functions for the CAPCS. The indicator unit was installed in the front cockpit and provided the pilot with appropriate indications of the CAPCS operating modes and submodes. The control unit was installed in the rear cockpit to give the operator the capability of selecting the desired CAPCS parameters.

The control unit incorporates four thumbwheel switches which allow the operator to make inflight modification of the spike and door schedules, the autopilot altitude hold gain, and the autothrottle KEAS hold gain. The thumbwheel switches are 10-position types, allowing for selection of settings 0 through 9. The 0 positions represent the nominal values. For each change of switch position the associated parameters are changed by a fixed amount. For the spikes, each successive position corresponds to 0.5 inch added to the spike schedule; for the doors the change is -0.05 duct pressure ratio units; for the autopilot and autothrottle gains, the change is 5 percent from the nominal value. A momentary action switch is provided in both the front and rear cockpits to enter the values established by the switch settings.

2.1.5 Pressure Transducers

2.1.5.1 Total Pressure Transducer. The total pressure transducer is a digital precision pressure transducer manufactured by Garrett Airesearch (Part No. 2100778-3). It has a range of 0 to 80 in. Hg absolute and has a static accuracy of $\pm$ 0.010 in. Hg or $\pm$ 0.02 percent total pressure, whichever is greater, over a pressure range of 1 to 80 in. of Hg. At pressure rates of change ($\dot{p}$) up to $\pm$ 0.3 in. Hg/sec, the error may be no greater than the sum of the allowable static error plus 0.050 second multiplied by $\dot{p}$. Following a maximum rate of change the transducer is required to be within the specific tolerance 0.1 second after the input has stabilized.

2.1.5.2 Static Pressure Transducer. The static pressure transducer is a digital precision transducer which is also manufactured by Garrett Airesearch (Part No. 2100776-3-1). It has a range of 0 to 36 in. Hg absolute and a static accuracy of $\pm$ 0.009 in. Hg over a pressure range of 0.322 to 31.0 in. Hg. At pressure rates of change ($\dot{p}$) up to $\pm$ 0.3 in. Hg/sec, the error may be no greater than the sum of the allowable static error plus 0.050 second multiplied by $\dot{p}$. Following a maximum rate of change the transducer is required to be within the specified tolerance 0.1 second after the input has stabilized.

2.1.5.3 Differential Pressure Transducers. Two analog quartz differential pressure transducers were used to measure angle of attack and angle of sideslip differential pressures, ΔP_α and ΔP_β, respectively. These transducers were "off-the-shelf" devices that were currently being used in the F-16 air data computer. They had been previously flight qualified by virtue of having met all MIL-STD-5400, Class 2X specifications. The transducers exhibit the following characteristics at environmental extremes:

Parameter	Specified Range
Pressure range	-25 to +25 in. Hg
Output	10V full scale
Power required	$\pm$ 15V DC, 0.8 watt max.
Accuracy	$\pm$ 0.1% full scale
Hysteresis	0.005% full scale
Acceleration sensitivity	0.01% full scale/g

2.2 BASIC DESIGN CONSIDERATIONS

The system design of CAPCS was driven by the requirements that (1) the system should not compromise flight safety, (2) the cockpit operation of the replaced analog subsystems should remain unchanged, and (3) the CAPCS installation should allow easy reversion to the analog configuration.

Flight safety considerations dictated which analog subsystems would be replaced with the digital system. For example, the SAS was not digitized because there was no readily obtainable backup SAS available. Also, the analog inlet control system computers contained the manual inlet control circuitry, and since it was decided to remove these computers, the analog manual inlet control function was retained by incorporating it into the CAPCS interface unit. The final flight safety consideration was the analog air data computer which furnished information to the SAS and cockpit instruments. An analog air data computer was retained to perform these functions so the digital computer thus furnished information only to those subsystems that were digitized. Therefore, none of the functions performed by the CAPCS impacted flight safety and backup capability was provided for each of these functions.

The CAPCS was invisible to the pilot; i.e., the cockpit operation of the centralized digital system was the same as the operation of the analog subsystems. The pilot interfaced with the autopilots via the Automatic Flight Control System (AFCS) function selector panel. The engage logic and the available submodes were the same as for the analog system. The selection of automatic inlet control, manual inlet control, and restart were provided by the same four control knobs, restart and throttle switches. The autothrottle control panel was the same for either digital or analog control. The only cockpit differences between the digital and analog systems were the addition of two circuit breakers, a CAPCS ON/OFF switch and a CAPCS FAIL annunciator that was added to the master caution panel. Operation of the CAPCS-controlled aircraft systems was thus essentially unchanged from the previous configuration except for the following procedural differences:

a. The CAPCS had to be turned on by the pilot at engine start and turned off before engine shutdown.

b. The inlet Manual Restart mode had to be selected for both takeoff and landing. (This action was necessary because one level of redundancy was lost in logic that kept the inlet spikes full forward at low speed when the analog inlet control was replaced with the CAPCS. There was concern that the inlet duct would collapse if the inlet spike moved full aft when the engine was at military power and the aircraft forward velocity was under 250 knots.)

c. If a CAPCS failure occurred the pilot had to immediately switch to manual control of the inlets.

The final consideration for the CAPCS design was that it be installed in such a manner as to allow easy reversion to the original analog configuration. The physical locations of the analog inlet control computer, autothrottle computer and AFCS computer on the normally configured aircraft are indicated in Figure 2-9. Prior to the installation of CAPCS the autothrottle control electronics and inlet control system analog computer were removed from the aircraft. The CAPCS digital computer and interface unit were then installed in the nose along with the ΔP_{α} and ΔP_{β} differential pressure transducers (see Figure 2-9). Both the computer and interface unit were installed on hinged mounts so that they could be rotated down for trouble shooting of interface unit through cables which previously interconnected the inlet control computer and autothrottle computer. Since the pitch and roll autopilot functions were now being handled by the CAPCS, only the SAS computer position of the AFCS needed to be retained. The pitch and roll autopilot computer modules were thus removed from the AFCS and replaced by dummy modules which merely served to maintain the required electrical interconnections. The CAPCS was then connected to this unit by cables. Thus the original analog configuration could be restored merely by removing the CAPCS units and the dummy modules, reinstalling the inlet control computer, the autothrottle and the pitch and roll computer modules, and reconnecting the units as before.

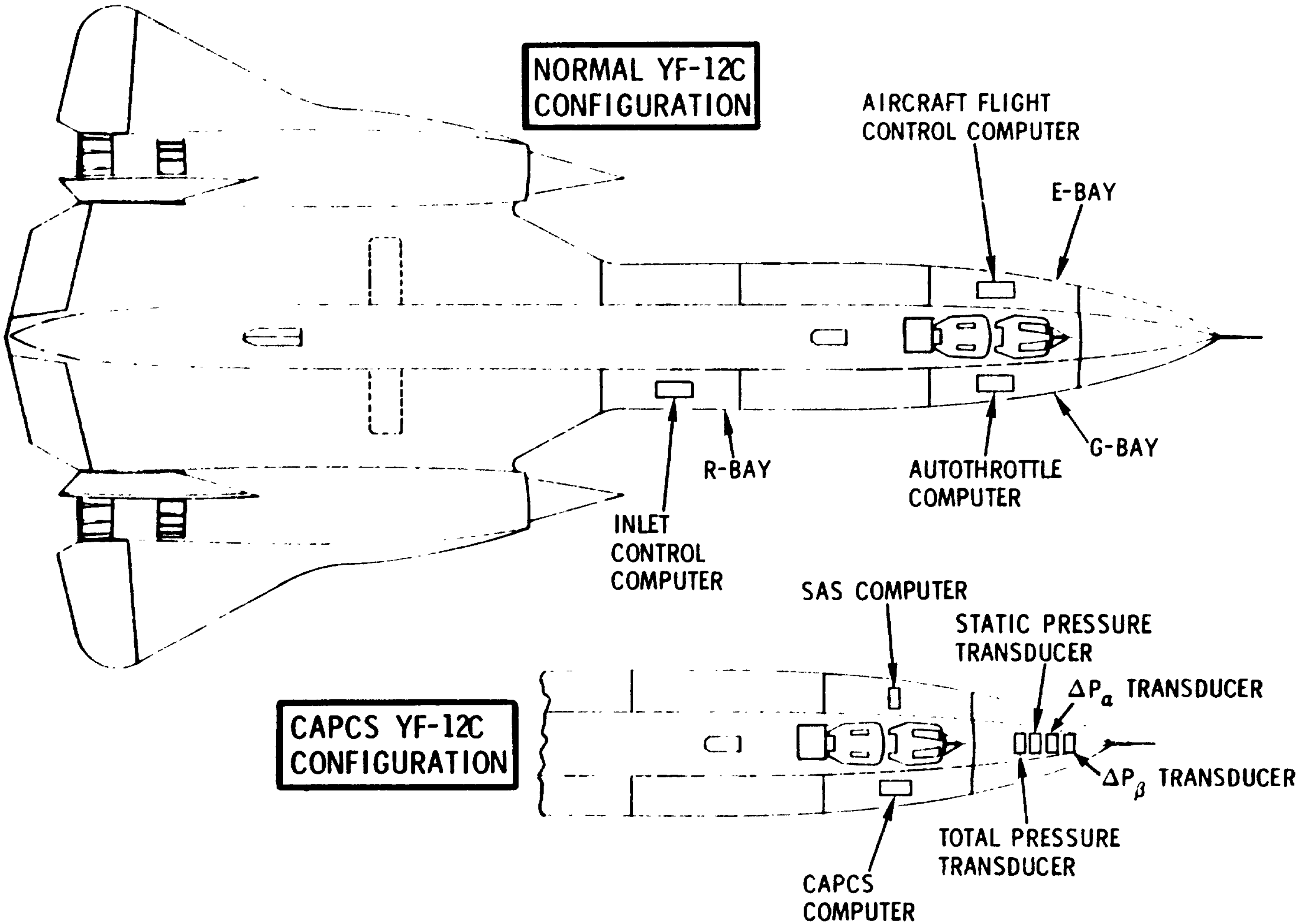


Figure 2-9. Equipment Component Locations for Normally Configured and CAPCS Configured YF-12C Aircraft

SECTION 3
SYSTEM DEVELOPMENT

3.1 SOFTWARE DEVELOPMENT

The development and integration of software for the CAPCS program was accomplished by Lockheed-ADP at the Lockheed Rye Canyon research facility. The software support facility at Rye Canyon consisted of the airborne Univac 1816 Digital Computer and the required commercial peripherals to support Univac's Level II support software. The computer was configured with eight I/O ports, a 32k core memory, and an ROM bootstrap loader which would accommodate either magnetic or paper tape. Figure 3-1 illustrates the hardware configuration which comprised the CAPCS software support facility. The capabilities of the computer resident support software are also itemized in Figure 3-1. The Rye Canyon facility was used to develop all of the operational and associated support utilities which are described in the following paragraphs.

3.1.1 Software Structure

Each CAPCS computer subsystem (air data computer, pitch autopilot, roll autopilot, autothrottle control system and inlet computer) is implemented by a set of module subroutines. The addresses of these modules form the set from which the running list elements are drawn. The modules are serviced by various support subroutines. The modules associated with each subsystem are listed in Table 3-1. The external inputs and output of the subsystems are given in Tables 3-2 and 3-3, respectively. Lists of the constants and schedules used and the intermediate calculations are given in Table 3-4 and 3-5.

The subsystem functions are split into modules on the basis of their usage and their dominant time response. For example, in the air data calculations, the calculations of aerodynamic gain are split off from the cal-

RESIDENT SUPPORT SOFTWARE

UNIVAC LEVEL II SUPPORT SOFTWARE	FUNCTIONS
MACRO ASSEMBLER FORTRAN COMPILER BATCH MONITOR	———
LIBRARIAN	LIST, COPY, DELETE, FIND EDIT, ADD, TERMINATE, PAUSE
LINKING LOADER	———
UTILITY ROUTINES	• ASC II CODED DECIMAL TO BINARY • BINARY TO ASC II CODED DECIMAL • ASC II TO FIELD DATA CHARACTER • FIELD DATA TO ASC II CHARACTER • ASC II OCTAL TO BINARY CONVERSION • BINARY TO ASC II OCTAL CONVERSION
SYSTEM TAPE GENERATOR	———
DEBUG ROUTINES	PRINTER DUMP, STORE CONTENT, BINARY DUMP, SNAPSHOT DUMP MASKED MEMORY SEARCH

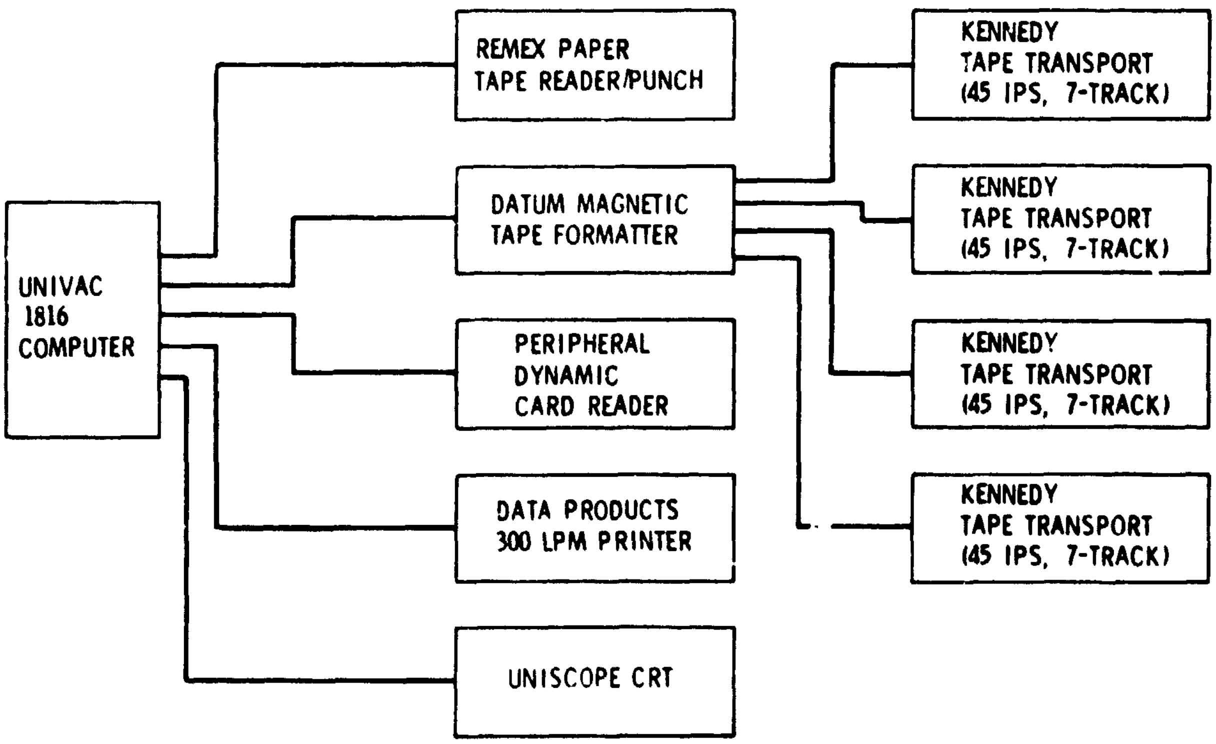


Figure 3-1. CAPCS Support Hardware/Software Configuration

TABLE 3-1. SUBSYSTEM MODULES

Subsystem	Module	Execution Rate (Hz)	Description Reference
Air Data Computer	ADCS 1	10	Appendix A-I
	ADCS 2	10	
	ADCS 3	10	
	ADCS 4	5	
Pitch Autopilot	PAPS 1	50	Appendix A-IV
	PAPS 2	5	
	PAPS 3	20	
	PAPS 4	20	
Roll Autopilot	LATAXN	50	Appendix A-III
	LATAXS	20	
Autothrottle Control System	ATCS	20	Appendix A-II
Inlet Computer	HOTBOX	100	Appendix A-V
	FORLPS	50	
	INLTSH	5	

TABLE 3-2. SUBSYSTEM EXTERNAL INPUTS

Module	Variable	Name	Computer	Units	Scale
AIR DATA COMPUTER					
ADCS1	Static pressure	P_s	PS$	in. Hg	40.0
ADCS1	Static pressure	P_{STAT}	PSTAT$	in. Hg	40.0
ADCS1	Total pressure	P_t	PT$	in. Hg	100.0
ADCS1	Total pressure	P_{TOT}	PTOT$	in. Hg	100.0
ADCS3	Angle of attack, differential pressure	ΔP_α	DACFA$	in. Hg	6.9
ADCS3	Angle of sideslip, differential pressure	ΔP_β	DBETA$	in. Hg	-3.95
PITCH AUTOPILOT					
PAPS1	Pitch gyro input	Q_G	QGYRO$	deg/sec	-4.80455
PAPS3	Pitch attitude	$\Delta\theta$	THERR$	deg	139 178
PAPS4	Trim actuator output	DEAP2	DEAP2$	deg	30.0
ROLL AUTOPILOT					
LATAXS	Roll attitude	ϕ	RLLAT$	deg	-45.8015
LATAXS	Bank angle	ϕ_{BK}	BNKAG$	deg	1.31818
LATAXS	Auto Nav	A/N	AUTNV$	deg	-42.8571
LATAXS	Roll attitude SUM	ϕ_Σ	PHISM$	deg	-180.0
LATAXS	Heading	ψ	HEAD$	deg	-183.299
LATAXN	Roll rate	$\dot{\phi}$	ROLLR$	deg/sec	-5.71738
AUTOTHROTTLE CONTROL SYSTEM					
ATCS	Mach/KEAS trim	$T_{M/K}$	MKTRM$	deg	-5.0
ATCS	Pitch attitude	θ_{INS}	INSTM$	deg	180.0
ATCS	Right engine trim	T_{RE}	RENTM$	deg	-10.0
ATCS	Left PLA	L_{PLA}	LPLAT$	in.	-0.58
ATCS	Right PLA	R_{PLA}	RPLAT$	in.	+0.58

TABLE 3-2. SUBSYSTEM EXTERNAL INPUTS (Continued)

Module	Variable	Name	Computer	Units	Scale
INLET COMPUTER					
HOTBOX	Duct pressure ratio (fulcrum position)		LPRSS LPRSC RPRSS RPRSC	110°/PRU - - -	2.0
HOTBOX	Duct pressure ratio (commanded)		DPRLSC DPRRSC	110°/PRU -	2.0
FDRLPS	E-core output E-core output		L2PE$ R2PE$	Vac	0.6 0.6
FDRLPS	Spike bias Spike bias		VLOCL$ VLOCR$	Vac Vac	20V/in. 20V/in.
FDRLPS	Inlet unstart Inlet unstart		USTL$ USTLR$	- -	1.0 1.0
FDRLPS	Duct error gain	K3D	K3D	-	1.0
INLTSH	Mach		MACH$	M	3.5
INLTSH	Angle of attack		ALPHA$	deg	14.0
INLTSH	Sideslip angle		BETA$	deg	6.0
INLTSH	Normal acceleration		DNZ	g's	2.5
INLTSH	Inlet discretes		HUSTR$	-	1.0

TABLE 3-3. SUBSYSTEM EXTERNAL OUTPUTS

Module	Variable	Name	Computer	Units	Scale
PITCH AUTOPILOT					
SWITCH	High KEAS warning	HIKEAS	RLYWD$	logical	
PAPS3	Autopilot input to SAS	DEAP1	DEAP1$	deg	2.3
PAPS4	Input to trim actuator	P_{TRM}	PTRMD$	logical	
ROLL AUTOPILOT					
LATAXN	Autopilot input to roll SAS	R_{SAS}	RLSAS$	deg	3.22195
SWITCH	Lateral autopilot cockpit	R_{AEM}	RLYWD$	logical	
INLET COMPUTER					
HOTBOX	Motor command		LDPRM$	Vac	± 33.0
HOTBOX	Motor command		RDRM$	Vac	± 33.0
FDRLPS	Door command		ERLFD$	mA	1.0
FDRLPS	Door command		ERRFD$		
INLTSH	Solenoid commands		SOLEN$	-	1.0
INLTSH	Spike extend/ retract commands		ERLSV$	mA	0.0275 mA/in.
INLTSH	Spike extend/retract commands		ERRSV$	mA	
INLTSH	Duct pressure		DPRL$	110°/ PRU	220°
INLTSH	Ratio commands		DPRR$		

TABLE 3-4. SUBSYSTEM CONSTANTS AND SCHEDULES

Module	Constant	Name	Computer	Value	Units
AIR DATA COMPUTER					
ADCS1	Standard pressure	P_0	PZERO	29.92126	in. Hg
ADCS1	H, range 1	b_1	MB1	147447.0	feet
ADCS1	H, range 1	n_1	-	5.2561	feet
ADCS1	H, range 2	d_2	D2	4901.85	feet
ADCS1	H, range 2	c_2	MC2	20505.85	feet
ADCS1	H, range 3	H_3	H3	82021.0	feet
ADCS1	H, range 3	c_3	-	236943.0	feet
ADCS1	H, range 3	b_3	B3	0.0245607	feet
ADCS1	H, range 3	n_3	-	11.3878	feet
ADCS1	M_{CL} constant	K_M	-	166.9216	
ADCS1	M_{CL} constant	$\hat{K}$	KHAT	0.726830	
ADCS1	V_e constant	K_v	KEQUIV	204.1018	feet/sec/ (in. Hg)1/2
ADCS1	KEAS conversion	K_{KV}	KKEAS	0.592484	knots/ (feet/sec)
ADCS1	Mach function	C_N (R)	CP	M_{CL} schedule	
ADCS1	Probe correction	DMP (M)	DMPCOR	Mach schedule	
ADCS3	α bias	α_b	ACPBS	5.8	deg
ADCS3	β bias	β_b	BETBS	0.0	deg
ADCS3	α function	K_{AI}(M)	KAI	α_o schedule	deg
ADCS3	α function	D_α (αo)		α schedule	deg
ADCS3	β function	K_{BI}(M)	KBI	β schedule	deg

TABLE 3-4. SUBSYSTEM CONSTANTS AND SCHEDULES (Continued)

Module	Constant	Name	Computer	Value	Units
AIR DATA COMPUTER					
ADCS4	Pitch attitude lag	τ_{THL} (log P_{STAT})	TTHL$	THL Schedule	sec
ADCS4	Pitch aero gain	P_{AG} (log P_{STAT} log (q_c))	P3GS$	PAP6 Schedule	deg/deg
ADCS4	Pitch integrated gain	$\theta \int_H$ (log P_{STAT})	THNTH$	A_{V3} Schedule	deg/sec/ ln (P_{STAT})
ADCS4	Pitch position gain	θ_H (log P_{STAT})	THETH$	A_{V2} Schedule	deg/ln (P_{STAT})
ADCS4	Mach rate gain	P_{MG} (log P_{STAT})	PGAIN$	M_{V1} Schedule	
ADCS4	G-limit	G_{LIM} (M)	GLIM$	H_{INT} Schedule	deg/sec
ADCS4	Mach trim schedule	γ_c (M)	GAMC$	Δ_{MT} Schedule	deg
ADCS4	Lateral heading gain	H_g (M)	HDMGS$	L_{V3} Schedule	
PITCH AUTOPILOT					
PAPS2	Altitude calculation	X_{KQ}	XKQ	440.0	deg/ln (P_{STST})/ sec
PAPS2	Altitude calculation	X_{KH}	XKH	0.5	deg/ln (P_{STAT})/ sec
PAPS2	Altitude calculation	X_{KIH}	XKIH	0.25	deg/ln (P_{STAT})/ sec
PAPS2	KEAS calculation	X_{KQ14}	XKQ14	65.0	deg/sec/ ln (V_e)

TABLE 3-4. SUBSYSTEM CONSTANTS AND SCHEDULES (Continued)

Module	Constant	Name	Computer	Value	Units
PITCH AUTOPILOT					
PAPS2	Bleed gain	X_{KBGN}	BLDGAN	0.02	deg/sec/knots
PAPS2	KEAS calculation	X_{KQ12}	XKQ12	10.0	deg/sec/ln (V_c)
PAPS2	Mach calculation	X_{KQ15}	XKQ15	65.0	deg/sec/ln (R-1)/sec
PAPS2	Mach calulation	X_{KQ13}	XKQ13	10.0	deg/sec/ln (R-1)
PAPS3	Attitude calculation	X_{KQ2}	XKQ2	0.5	deg/deg/sec
PAPS3	Attitude calculation	X_{KQ4}	XKQ4	0.15	deg/deg/sec
PAPS3	Attitude calculation	X_{KQ5}	XKQ5	1.0/3.0	deg/deg/sec
PAPS3	Attitude calculation	X_{KQ8}	XKQ8	0.5	deg/deg/sec
PAPS3	Output calculation	X_{KQ7}	XKQ7	1.0	deg/deg/sec
PAPS3	Output calculation	X_{KQ7}	XKQ7P	0.7	deg/deg/sec
AUTOTHROTTLE CONTROL SYSTEM					
ATCS	Mach gain	M_{GAIN}	MGAIN	-300.0	deg/Mach
ATCS	KEAS gain	K_{GAIN}	KGAIN	-2.3	deg/knots
ATCS	High pass gain	H_{IP}	HIPSGN	6.5	deg/knots
ATCS	INS gain	G_{INS}	INSGN	2.0	deg/deg
ATCS	Proportional gain	K_{PROP}	PROPOT	3.0	deg/deg
ATCS	Control gain	K	K	1.0	deg/deg
ATCS	Integrator gain	G_{INT}	-	0.025	deg/sec/deg
ATCS	Feedback gain	K_S	MKS	17.3	deg/in.

TABLE 3-5. CALCULATED VARIABLES

Module	Variable	Name	Computer	Units
AIR DATA COMPUTER				
ADCS1	Normalized pressure	R_s	RS$	in. Hg
ADCS1	Pressure altitude	H	H$	feet
ADCS1	Impact pressure	q_c	QC$	in. Hg
ADCS1	Pressure ratio	R	PRATO	
ADCS1	Mach, uncorrected	M_{cc}	MCC	
ADCS1	Mach, probe corrected	M	MACH$	
ADCS1	Dynamic pressure	q	Q$	in. Hg
ADCS1	Equivalent velocity	V_e	VEQIV$	feet/sec
ADCS1	Equivalent velocity	K_s	KEAS$	knots
ADCS1	Bleed line bias	K_B	KSMHB$	knots
ADCS2	Altitude rate	d/dt(H)	HDOT$	feet/sec
ADCS2	Altitude position error	$\Delta \ln (P_{STAT})$	DLPS$	$\ln (P_{STAT})$
ADCS2	Keas position error	$\Delta \ln (V_e)$	DLVE$	$\ln (V_e)$
ADCS2	Mach position error	$\Delta \ln (R-1)$	DLRM$	ln (R-1)
ADCS2	Altitude rate error	$d/dt (\ln (P_{STAT}))$	DLPSD$	$\ln (P_{STAT})$/sec
ADCS2	Impact pressure rate	$d/dt (\ln (q_c))$	DLQCD	$\ln (q_c)$/sec
ADCS2	Keas rate error	$d/dt (\ln (V_e))$	DLVEDS	$\ln (V_e)$/sec
ADCS2	Mach rate error	d/dt (ln (R-1))	DLRMD$	ln (R-1)/sec
ADCS3	Angle of attack, uncorrected	α o	ALP	deg
ADCS3	Angle of attack	α	ALPHA$	deg
ADCS3	Angle of sideslip	β	BETA$	deg
ADCS4	Pressure log	$\log (P_{STAT})$	LOGPS	$\log (P_{STAT})$

TABLE 3-5. CALCULATED VARIABLES (Continued)

Module	Variable	Name	Computer	Units
AIR DATA COMPUTER				
ADCS4	Pressure log	$\log(q_c)$	LOGQC	log (qc)
PITCH AUTOPILOT				
PADS1	Notch output	Q_{BD7}	QBD7$	deg/sec
PADS2	Altitude variable	A_{V1}	ALTV1	deg
PADS2	Altitude variable	A_{V2}	ALTV2	deg
PADS2	Altitude variable	PAPS	PAPS	deg
PADS2	Altitude variable	A_{V3}	ALTV3	deg/sec
PADS2	KEAS variable	K_{V1}	PAPK1	deg/sec
PADS2	KEAS variable	K_{V2}	KESV2	deg/sec
PADS2	KEAS variable	K_{V3}	KESV3	deg/sec
PADS2	KEAS variable	K_{V4}	KESV4	deg/sec
PADS2	Mach variable	M_{V1}	MACV1	deg/sec
PADS2	Mach variable	M_{V2}	MACV2	deg/sec
PADS2	Mach variable	M_{V3}	MACV3	deg/sec
PADS2	Summation	H_{DS}	HDSUM	deg/sec
PADS2	Integrator input	PAP2		deg
PADS2	Integrator output	H_{INT}	INTOT	deg
PADS2	Integrator output	PAP3	PAP3	deg
PADS2	Summation	P_{SM}	PAPSM	deg
PADS2	Limited output	PAP4	PAP4$	deg
PADS3	Log input	T_{HLI}	THLI	deg
PADS3	Log output	T_{HL}	THL	deg
PADS3	Attitude variable	T_{V4}	THV4	deg
PADS3	Attitude variable	T_{HCI}	THCMI	deg
PADS3	Attitude variable	PAP6	PAP6	deg

TABLE 3-5. CALCULATED VARIABLES (Continued)

Module	Variable	Name	Computer	Units
PITCH AUTOPILOT				
PADS3	Attitude variable	PAP7	PAP7	deg
PADS3	Fader	PAP8	PAP8	deg
PADS3	Lag output	PAP9	PAP9	deg
PADS3	Hysteresis output	PAP10	PAP10$	deg
PADS3	Lag output	PAP12	PAP12	deg
PADS3	DEAPI input	D_{PIN}		deg
PADS3	Autopilot input to SAS	DEAPI	DEAPI$	deg
PADS4	Mach trim error	Δ MT	MTERR$	deg
PADS4	Lag output	M_{TV1}	MTV1	deg
PADS4	Hysteresis output	M_{TV2}	MTV2	deg
PADS4	Trim actuator input	P_{TRM}	PTRMO$	
ROLL AUTOPILOT				
LATAXS	Heading error	$\Delta \psi$	HDERR	deg
LATAXS	Heading variable	L_{V3}	LATS3	deg
LATAXS	Attitude error	$\Delta \phi$	PHIER$	deg
LATAXS	Steering input	L_{V4}	LATS4	deg
LATAXS	Steering command	L_{SR}	LATSR$	deg
LATAXS	Limiter input	L_{V6}	LATS6	deg/sec
LATAXS	Limiter output	L_{V7}	LATS7	deg/sec
LATAXS	Integrator output	L_S	LTINT	deg
LATAXS	Attitude output	L_{OUT}	LATOT$	deg
LATAXN	Notch input	R_{IN}	RLRIN	deg/sec
LATAXN	Notch output	R_{NH}	RLRNCH	deg
LATAXN	Lag output	R_{LG}	LTLG2	deg
LATAXN	Notch line output	L_{NCH}	LATNH$	deg
LATAXN	SAS input	R_{SAS}	RLSAS$	deg

TABLE 3-5. CALCULATED VARIABLES (Continued)

Module	Variable	Name	Computer	Units
AUTOTHROTTLE CONTROL SYSTEM				
ATCS	Mach input	ΔM	DMACH$	
ATCS	KEAS input	ΔK	DKEAS$	knots
ATCS	Control input	A_{TIN}	ATINP	deg
ATCS	Lag output	A_{TLG}	ATLAG1	deg
ATCS	Filter output	A_{TEL}	ATFIL	deg
ATCS	High pass output	A_{THP}	ATHIPS	deg
ATCS	INS input	A_{TINS}	ATINS	deg
ATCS	Summation	A_{TS1}	ATSM1	deg
ATCS	Washout output	A_{TWO}	ATWSOT	deg
ATCS	Summation	A_{TS2}	ATSM2	deg
ATCS	Integrator output	$A_{T\int}$	ATSINT	deg
ATCS	Control input	CONIN	CONIN	deg
ATCS	Right actuator input	R_{AT}	RTACT$	deg
ATCS	Right hysteresis output	R_{ITO}	-	-
ATCS	Right feedback	R_{FB}	RTFDBK	deg
ATCS	Left actuator input	L_{AT}	LFACT$	deg
ATCS	Left hysteresis output	L_{HO}	-	-
ATCS	Left feedback	L_{FB}	LFFDBK	deg
ATCS	Right trim	T_{MIN}	-	deg
ATCS	Tracking moniter	T_{MON}	TRKMON	deg

culations of Mach and dynamic pressure because they are totally separate and distinct and because each set of calculations has its own sampling rate requirement. This type of segmentation was appropriate to the developmental nature of the project; i.e., the software was so structured as to provide a convenient method of altering execution rates of any of the program segments, thereby affording sufficient facility to experiment with the timing of each module. Segmentation also had the effect of making the program easier to modify and control. The specific segmentation and rates were determined by the engineering staff associated with the CAPCS program.

The subroutines are modeled as closely as possible to the description, flow charts and equations that govern the existing analog system, with the exception of the inlet computer where more extensive modifications were required to achieve the required operational characteristics. Modifications resulting rom the experiences of the preflight checkout and flight test results were r ade, but these usually amounted to a clarification rather than a restructuring. No attempt was made to reformulate the problem (with the exceptions discussed in the inlet control system description in Appendix A), although it may have made for better code. For example, the mixture of logarithms to the base 10 and natural logarithms of pressures, which were given in various units, were not systematized. This was done to avoid confusing the existing documentation and to avoid the confusion that may have arisen in checkout, since the system had to be verified against an existing simulation.

The auxiliary subroutines called are of three types: interface manipulation, Tustin calls, and subroutines to calculate specific mathematical functions. The interface routines format the data coming through the interface. The Tustin routines are discussed in Appendix C. Standard mathematical functions, square root, natural logarithms, table lookup, etc., were developed and tailored to the specific requirements of the system.

3.1.2 Executive Functions

The CAPCS executive functions are divided into two areas:

the supervisory and the run time. Using the supervisory functions and the utilities, the operator can modify and experiment with the system and can also control the operating modes. The run time functions are used to control the real time operation of the system. They were developed to provide the user with a great deal of flexibility. This was necessary because of the developmental nature of the CAPCS project.

The supervisory section is controlled by writing codes to the control device. There are two classes of codes. One class is used for the standard utilities, inspect and change, dumps, etc; the other class is used for special operating functions. Of these, the most important are C, H and Z. H is the initial condition command. All of the subsystems and modules are initialized. In any of the routines that use Tustin implementations, all of the Tustin coefficients are calculated for the current system clock rate. C is the operate command. Execution of the run time list is begun from the current state. This makes it possible, during preflight checks for example, to run, go to a hold condition, inspect and possibly change the configurations, and then continue from the hold point. Z is used to make the transformation into the flight system before takeoff.

The run time system is a real time priority system driven by the real time clock. A priority scheme was required to preserve the integrity of the calculations; however, it had to be flexible because of the developmental nature of the task. In many areas, especially the inlet and door circuits, it was not sufficiently clear during the design phase what the response rates would be. Therefore it was necessary that the run time system be able to accommodate experimental changes without undergoing any major redesign.

The calculation subroutines for the various subsystems (air data computer, pitch autopilot, roll autopilot, autothrottle control system and computer) are assigned to a running list according to their required rate of execution. There was allowance for eight list elements and up to eight subroutines could be assigned to each list element. Each of the list elements is scheduled according to its required execution rate.

The scheduling algorithm for the list elements builds a double-buffered queue based on the required execution rate. The queue is driven by the real time clock. With the clock set at 200 Hz, the queue is interrogated every 5 milliseconds. If an event is scheduled it is started. If nothing is scheduled any necessary background bookkeeping is done.

Double buffering is used so that the next event queue can be built without affecting the processing of the current queue. The rebuild is done when the operating system is waiting for the next execution.

If a list is not completed by the time the next list is scheduled a new list item is built from the environment at the point of interruption. It is placed into the event queue according to the list event priorities. Only if the list item is not completed before it is scheduled again is there a time out error.

Since some of the list elements do have auxiliary subroutines that are shared, the Tustin routines for example, these routines are made reentrant. This is accomplished by keeping the temporary storage of the routines in the general registers. These are saved as part of the environment when a subroutine is interrupted and restored when it is recalled.

3.1.2.1 Differences is Operating Systems. There were two environments for the CAPCS systems. At the Lockheed Rye Canyon laboratory, CAPCS was linked to the hybrid facility YF-12 real time simulation. At the NASA Dryden Test Site, Edwards AFB, CAPCS was linked to the aircraft. The system software for the two systems was identical except for the supervisory section. There was no change in the run time system. The software differences were straightforward. At Rye Canyon, a printer and Uniscope display were available. At Edwards, only a Terminet was available. The only change required to transform the system was to change the I/O channel driver assignments, the IOPAK module being required for Rye Canyon and the FIOPAK module for Edwards. The drivers not required for the Edwards system were not put on the system tape. This was done to minimize the tape length.

One other important difference in the Edwards system was that the AUTO RESTART cell (0177) was loaded with the address of the start of the program. Thus when the computer power was turned off and then back on, the program automatically restarted.

3.1.3 PMASK

A special routine known as PMASK was developed to filter out unreasonable static and total pressure readings which are prone to occur occasionally. Thus the static and total pressure readings are processed through PMASK before use. Readings that are within preestablished limits are passed; readings that exceed these limits are rejected. PMASK is designed to eliminate ridiculously low pressure readings or those where the rate of change is excessive, thereby rendering the data invalid. If the total pressure falls below 0.3906 in. Hg or the static pressure below 0.1563 in. Hg, the last acceptable reading is used. Similarly, if the total pressure changes more than 0.78125 in. Hg or the static pressure more than 0.3125 in. Hg in one sample interval (100 milliseconds), the last acceptable reading is used.

3.2 HARDWARE DEVELOPMENT

3.2.1 Airborne Computer

Even though the Univac 1816 Digital Computer Set* (Figure 3-2) was "off the shelf," minor modification and special testing were required. For example, the construction of the aircraft requires that the surfaces of any installed equipment that comes in contact with the aircraft structure may not be cadmium-plated. As a result of this requirement all such materials were replaced on the computer. Also, from a special testing standpoint, the computer was required to operate at 55,000 feet altitude and at MIL-E-5400, Class 2X, temperature ranges. Since the 1816 computer had been qualified at MIL-E-5400, Class 1 only, special testing was performed to ensure that no problems would be

* See reference 7.

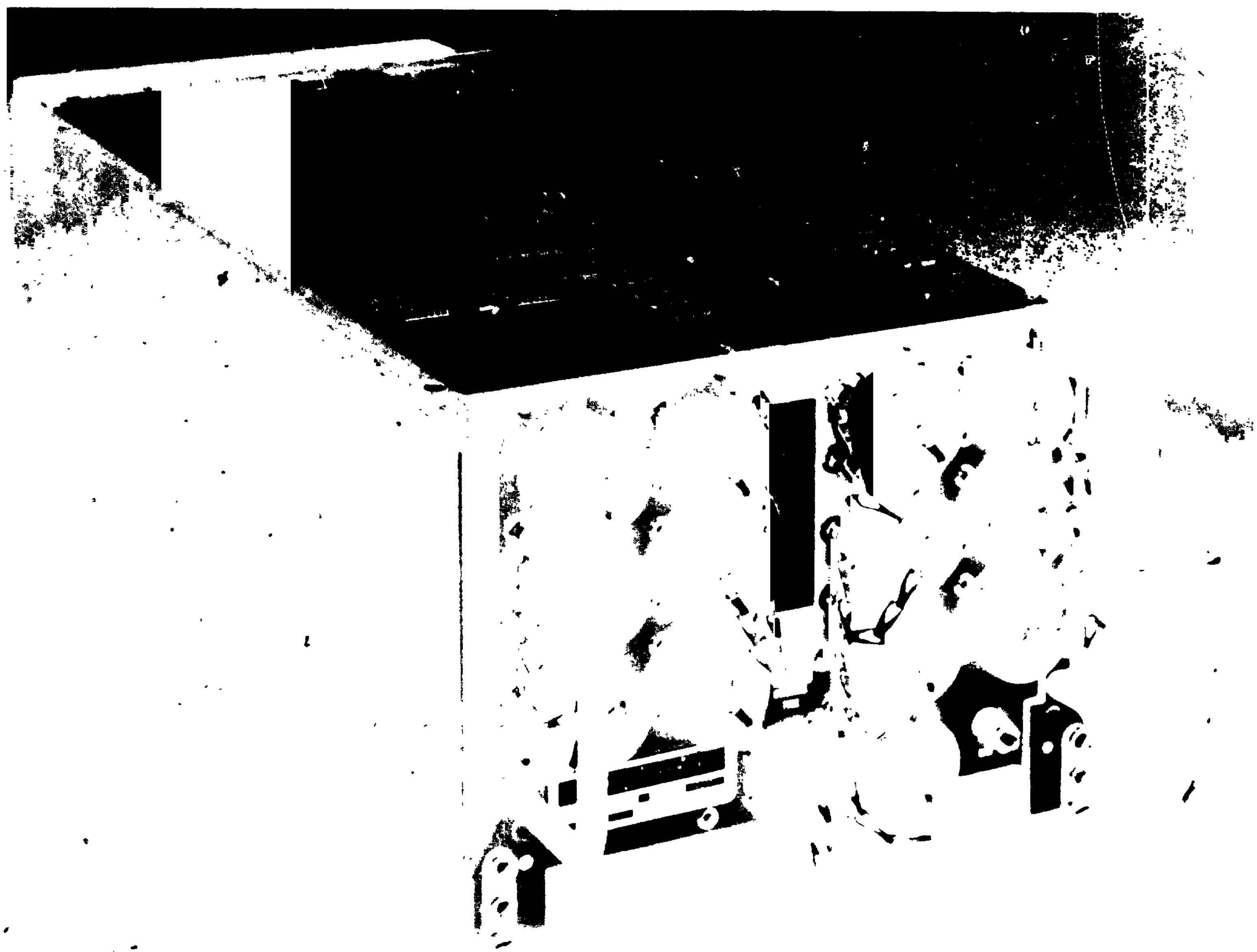


Figure 3-2. Univac 1816 Digital Computer Set

ORIGINAL PAGE IS
OF POOR QUALITY

encountered at the more severe environments. As a result of these special tests, a thermal problem was revealed in the power supply. The power supply was built into the base cover to the computer. The base cover, therefore, acts as a heat sink. To dissipate the heat more quickly, the thickness of the base cover had to be increased. This modification enabled the computer to meet the more severe environmental conditions.

After delivery of the computer and during development of the operational software, a performance problem was encountered. The execution of either a floating point add or subtract during a byte I/O transmission caused faulty execution of the instruction. A microcode change rectified this problem. Besides the design deficiencies mentioned, only two other hardware failures were experienced in two computers in three years. These involved the stack and an integrated circuit on the real time clock subassembly.

3.2.2 Interface Unit

The interface unit* (Figure 3-3), which was supplied by Minneapolis-Honeywell, was developed in two stages. In the first stage a laboratory version was supplied for integration and simulation use at Rye Canyon. The laboratory version had the same mechanical form factor as the final version but did not have the electronics needed to provide manual inlet backup, autopilot interlocks, analog servo loop closures for inlet spikes and doors, and aircraft PCM interface. Use of the laboratory version brought out some design deficiencies which were corrected in the final airborne version. The three areas of redesign involved the synchro-to-digital converters, the operation of the unit with respect to the computer, and the internal grounding philosophy.

The synchro-to-digital converters used in the laboratory version were hybrid modules which converted the synchro signal into a binary number representing angular shaft position. These modules were manufactured in the United Kingdom and were highly unreliable. The design was changed to Scott-T transformers with sample and hold circuits. The DC signals of the

* See reference 8.

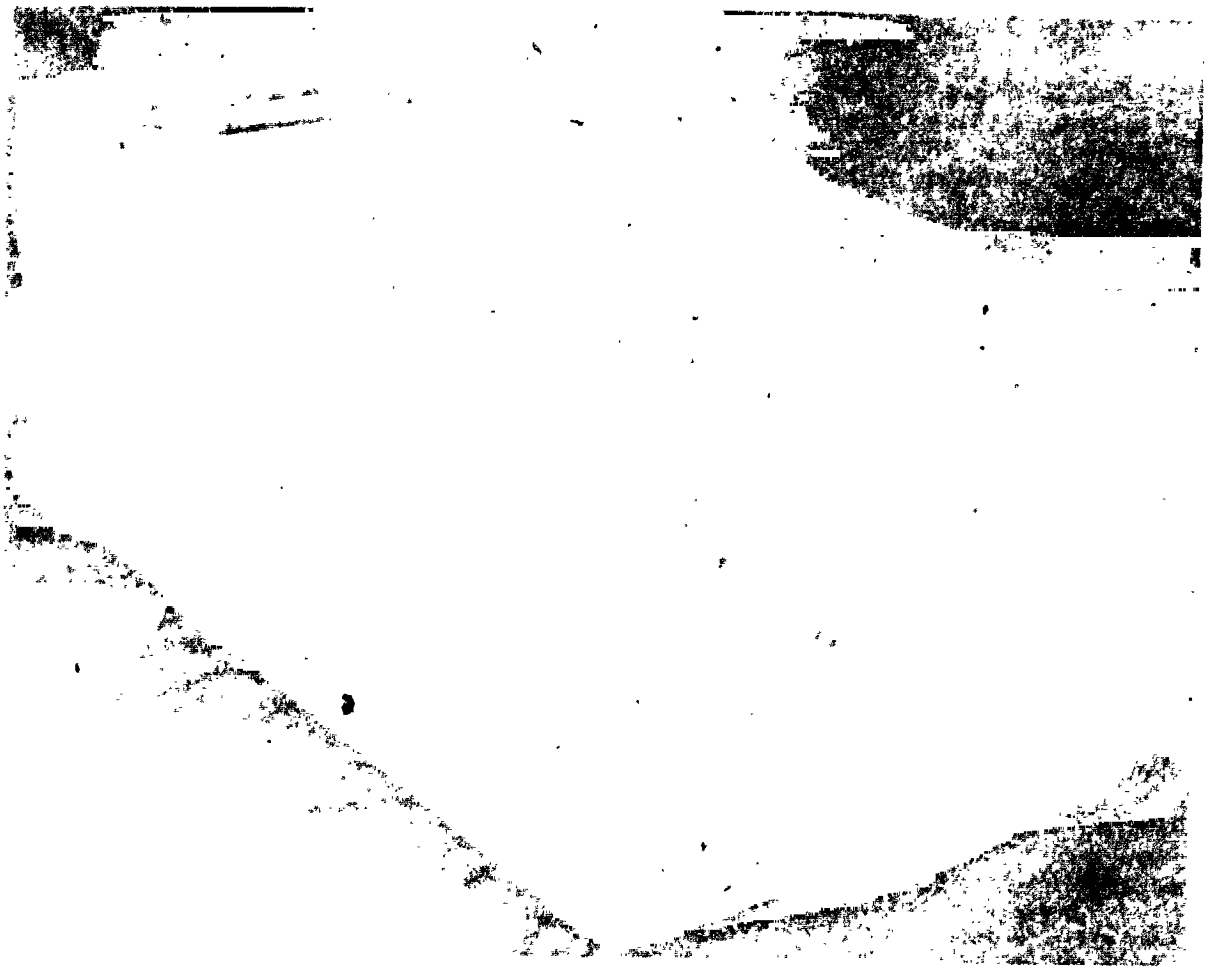


Figure 3-3. CAPCS Interface Unit

sample and holds were integrated into the available analog-to-digital converters to produce the sine and cosine of the angle. This process required additional processing time to produce the angle value, but the availability of trigonometric hardware made the angular processing time insignificant.

The I/O philosophy of the operational software was based on independence from interface unit timing. However, the laboratory version of the interface unit initiated a conversion cycle with a command from the computer. The operational software initiated the conversion cycle 108 times per second and proceeded with the execution of the software modules. Depending upon where the interface unit was in its conversion sequence when the respective reference peak occurred (AC conversion was based on peak detection), and when the operational software fetched, there could be staleness in the data of 75 milliseconds. This affected the frequency response of the system. Based on this experience, the final version of the interface was redesigned to free run, and thus all parameters were now converted at a rate of 400 times per second. Although this helped considerably, data staleness on the order of 0 to 2.5 milliseconds could still result from the asynchronism of the computer and interface unit operations.

The final area that underwent redesign was the internal grounding in the interface unit. This was done to reduce system noise. Laboratory tests earlier had revealed that within the laboratory environment there was approximately 80 to 350 millivolts of noise on every signal line. Investigation revealed that the laboratory cable trunking system and laboratory grounding caused the majority of the noise. An additional noise source was found to originate within the interface unit itself and was shown to be caused by the interconnection of the AC power ground and the DC power ground. (The DC power is used for the solenoid driver and also provides backup power for the manual inlet system.) Consequently the two grounding systems were isolated to reduce the system noise. Unfortunately this resulted in a 300-millivolt potential difference between the two grounding systems. Because of this potential difference, the solenoid drivers were redesigned for high noise rejection.

SECTION 4
SYSTEM TEST RESULTS

4.1 GENERAL TEST REQUIREMENTS

Since the CAPCS is a digital replacement for existing operational analog systems, the available design and performance data for these systems was used as the basis for evaluating the CAPCS performance. This evaluation was conducted in four test phases: open-loop tests, closed-loop tests, preflight tests and flight tests.

Open-loop testing concentrated on algorithm and schedule evaluations. The mathematical algorithms were statically checked. The input numbers were typically set up manually through the CRT terminal. That portion of the software under test was then executed and halted upon completion of the function. The results were either displayed on the CRT terminal or printed out on a line printer. These results were then compared with known criteria to evaluate accuracy. The accuracy goal for mathematical algorithms was five significant places. For algorithms or portions of the software that were frequency dependent, a BAFCO Servo Analyzer was used to verify that the digital implementation of a transfer function had sufficient gain and phase margins. Figure 4-1 illustrates the test setup for the open-loop frequency evaluation tests.

Gain, position and duct pressure ratio schedules were evaluated by driving the input to the schedule with a ramp generator and plotting the resulting output of the schedule determination software on analog strip charts. Figure 4-2 illustrates the test setup used for schedule evaluation.

After the open-loop test was completed, closed-loop testing was conducted with a simulated aircraft and simulated autopilot systems. The simulated aircraft and autopilot systems had gone through extensive cross-checking with actual flight data. The objective of the closed loop testing was to (1) duplicate the simulated/autopilot performance with the CAPCS implementation

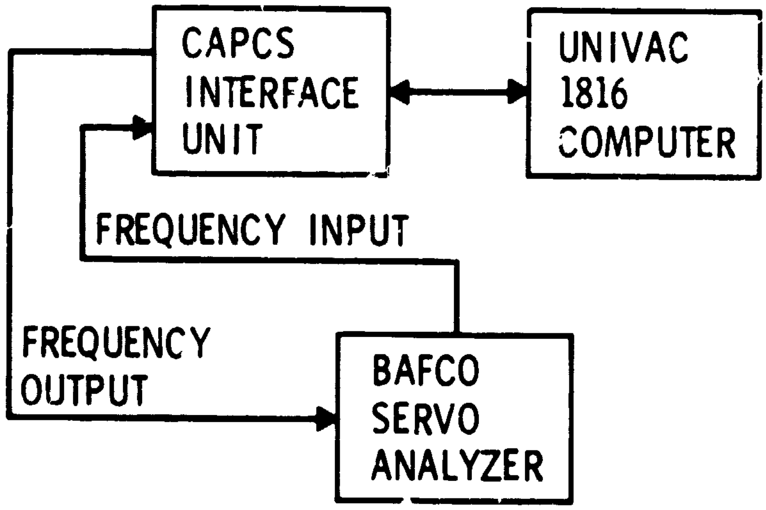


Figure 4-1. Open Loop Frequency Evaluation Test Setup

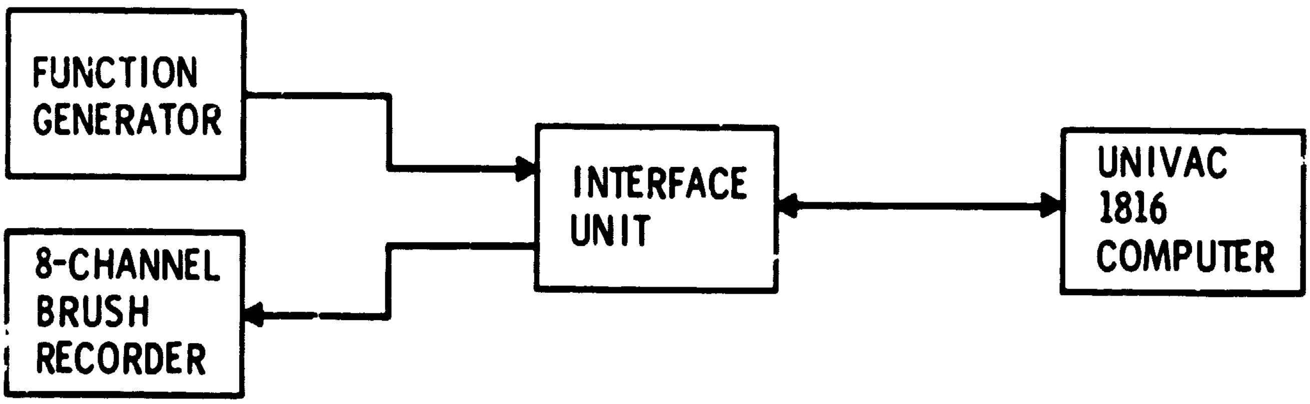


Figure 4-2. Open Loop Schedule Evaluation Test Setup

of the autopilot, and (2) to ensure that the aircraft remained stable despite inlet unstarts and turbulent conditions.

The CAPCS equipment was interfaced with the Rye Canyon simulation equipment through the Rye Canyon trunk system. A patching rack was developed to provide the interface between the CAPCS cabling and the Rye Canyon trunks. All of the inputs and outputs of the CAPCS interface unit and the Rye Canyon trunk connections were brought out to banana jacks on the patching rack. This arrangement made it convenient to selectively monitor and record all signals and provide external stimulus. Figure 4-3 depicts the hardware arrangement at Rye Canyon for the closed loop, simulated aircraft tests.

The Rye Canyon tests resulted in the release of the operational flight program for the CAPCS. From that point on the operational software was under configuration control. Subsequent tests centered around the aircraft and aircraft subsystems.

The main purpose of the preflight tests was to verify the electrical and functional characteristics of the CAPCS while operating in conjunction with actual aircraft subsystems. The hardware configuration for this preflight checkout is shown in Figure 4-4. The CAPCS preflight checkout procedures were fashioned around the existing preflight procedures which are currently being used for the analog system. These procedures are contained in Appendix I.

Successful completion of the preflight tests marked the start of the flight test phase of the program. The main objective of the flight tests was to demonstrate that the CAPCS was capable of performing as well as the analog subsystems it had replaced. This demonstration thus encompassed the entire flight envelope of the YF-12 aircraft. To aid in evaluating the results of this test phase, additional data retrieval capabilities were added to the aircraft and the operational flight software.

Flight data from the CAPCS consists of two sets of parametric

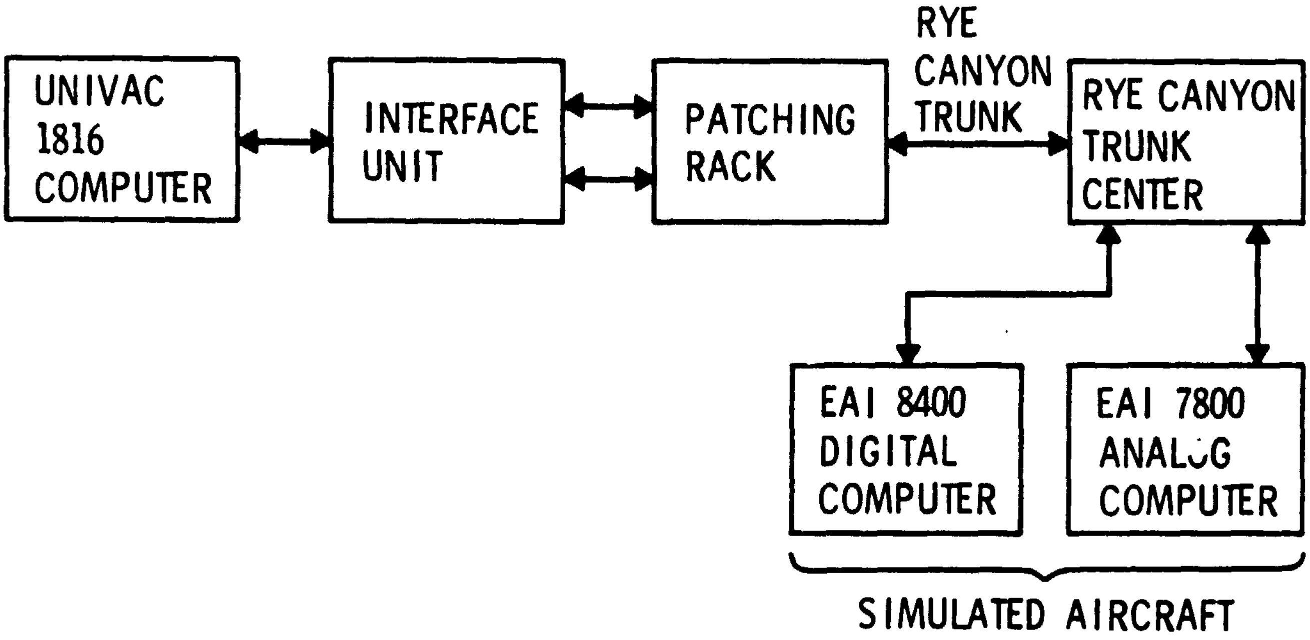


Figure 4-3. Closed Loop CAPCS Simulation Test Setup

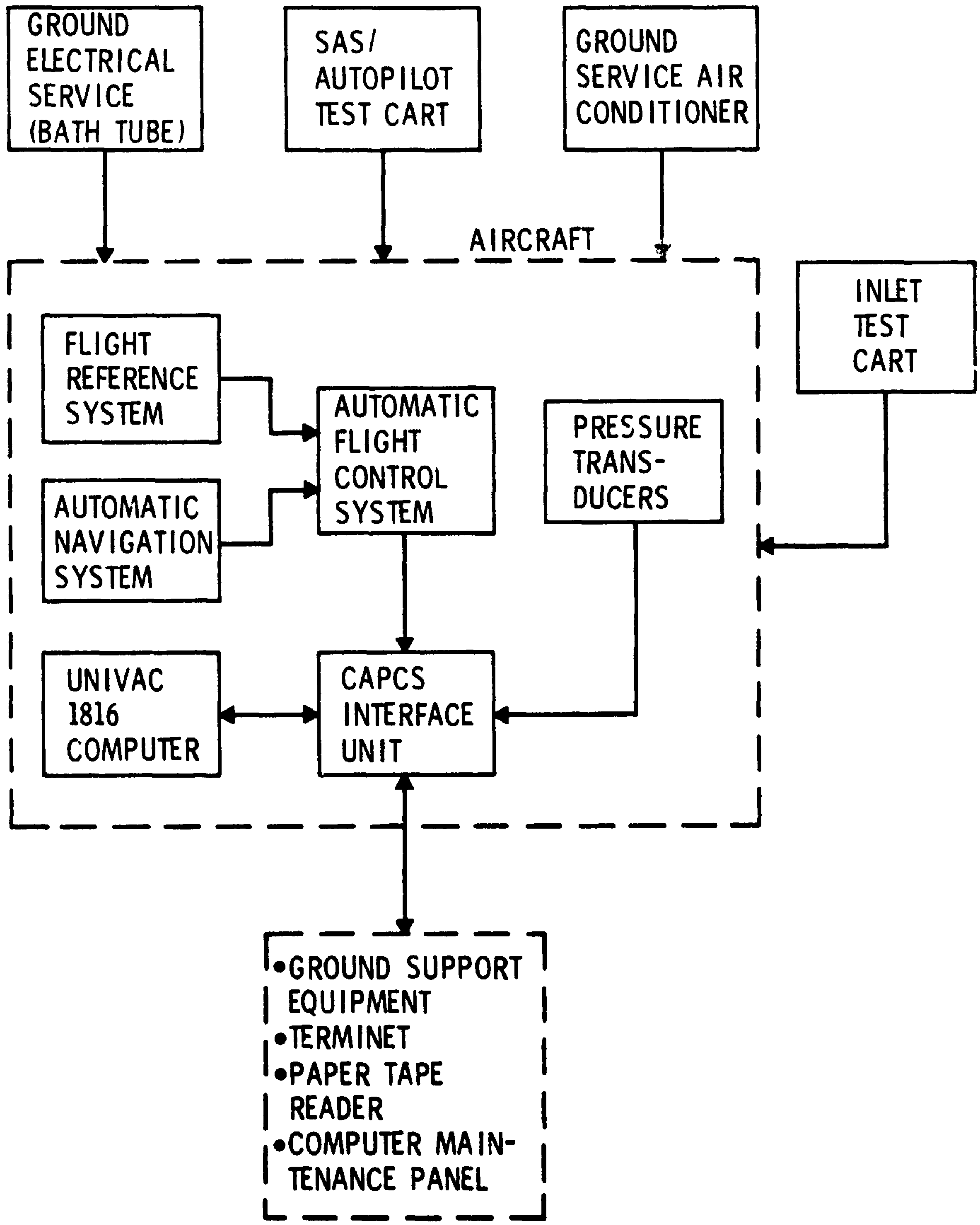


Figure 4-4. Test Setup for Preflight Testing

data, both of which are retrieved from the normally installed aircraft instrumentation. One set of data is available for analysis in real time and the other is recorded aboard the aircraft on one track of an analog data recorder for postflight analysis. The data intended for postflight analysis consist of a serial pulse code modulation (PCM) stream of data from the CAPCS interface unit which is comprised of internal system parameters. Selection of the parameters to be recorded was based on their comparative value in troubleshooting any problems that might arise during flight. (See Appendix E, pages E-9 and E-10, for the postflight parameter data list.)

The real time data are also recorded aboard the aircraft but are simultaneously telemetered to a ground station, where the data are recorded on a strip chart and made available for immediate use as needed. To accommodate the real time data requirements of the CAPCS, 16 analog channels were added to the existing instrumentation and the information contained therein is under program control by the CAPCS computer. The computer selects one of 10 sets of 16 parameters in response to a switching action by the RSO in the aft cockpit. Each set of parameter data contains specific information which ground personnel used to evaluate the performance of the subsystem under test in real time. The sets of real time parameter data are listed in Appendix E, pages E-13 thru E-22. Figure 4-5 illustrates the instrumentation configuration for real time data retrieval.

4.2 OPEN LOOP TESTS

4.2.1 Frequency Response Tests

Open loop frequency response tests of selected transfer functions were used as a tool to determine how well the digital mechanization of a transfer function compared with its analog counterpart. Figures 4-6 through 4-11 are representative of the results of one of these tests. The transfer function used in this example is the lag-lead network ($\frac{1.0 + 0.02S}{1.0 + 0.24S}$) from the inlet forward door loop.

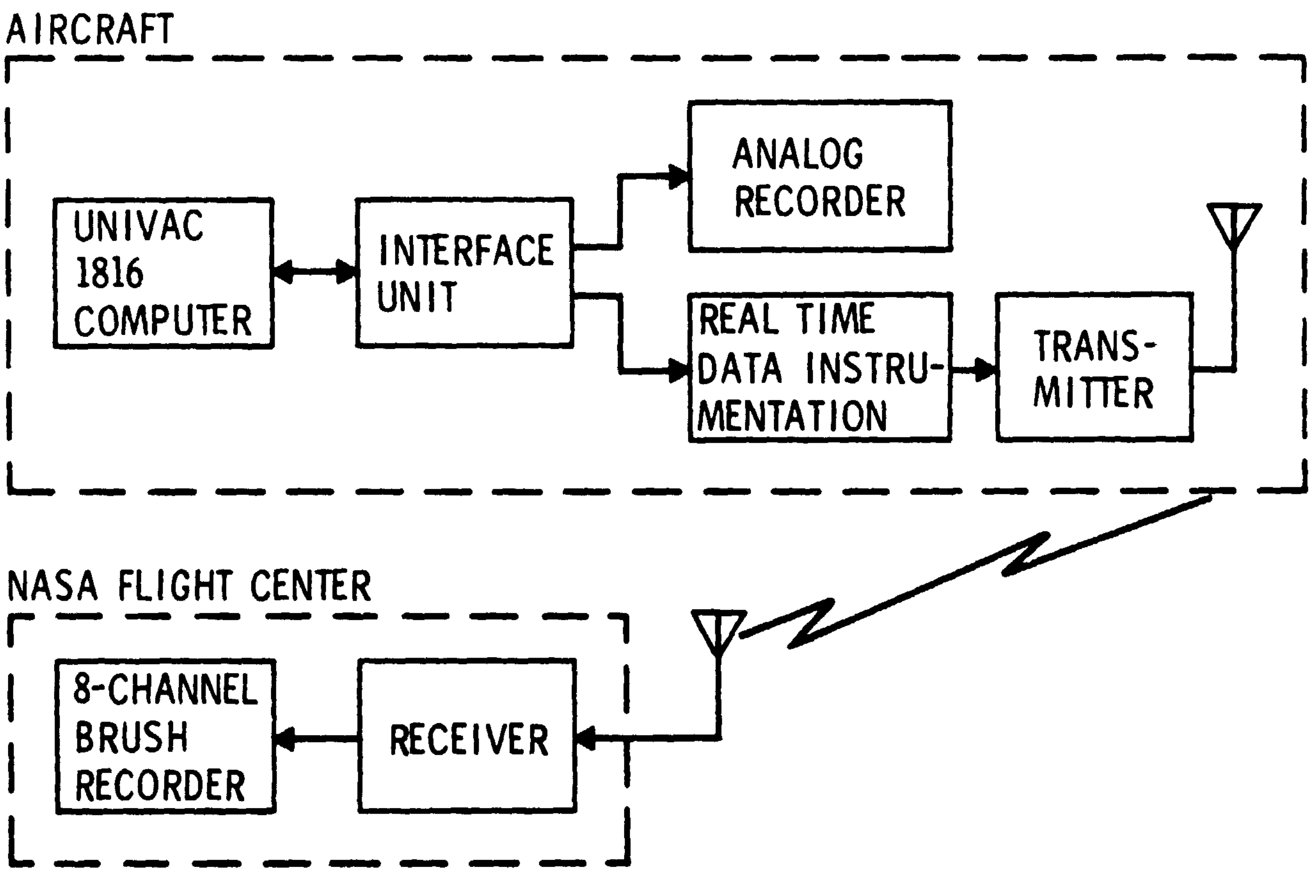
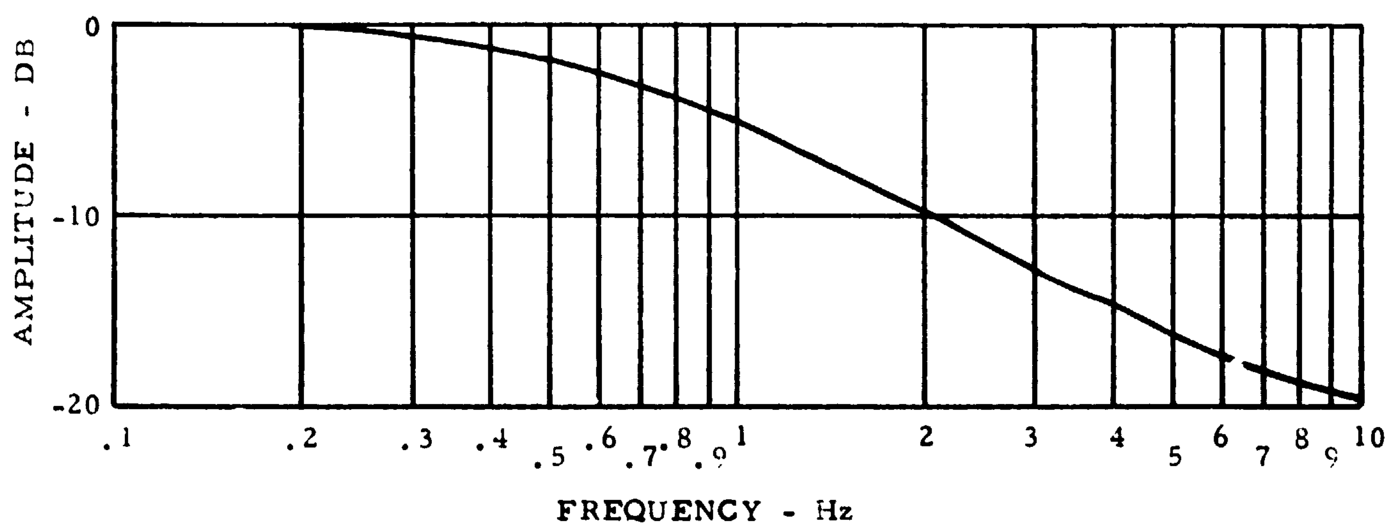
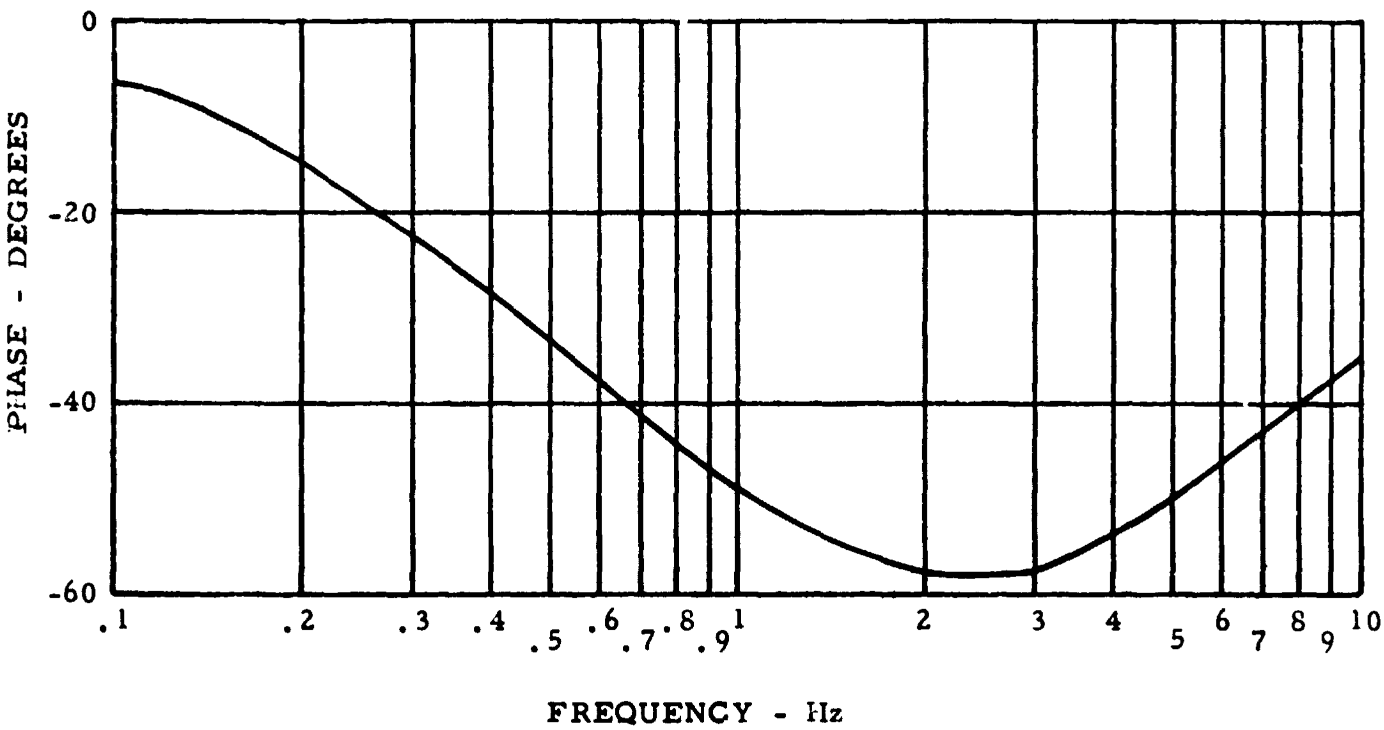


Figure 4-5. Instrumentation Configuration for Real Time Parameter Data Retrieval



Transfer Function: $\dfrac{1.0 + 0.025}{1.0 + 0.245}$

Figure 4-6. Plot of Amplitude vs Frequency for Forward Door Loop Lag-Lead Network, Theoretical Response



Transfer Function: $\dfrac{1.0 + 0.02S}{1.0 + 0.24S}$

Figure 4-7. Plot of Phase vs Frequency for Forward Door Loop Lag-Lead Network, Theoretical Response

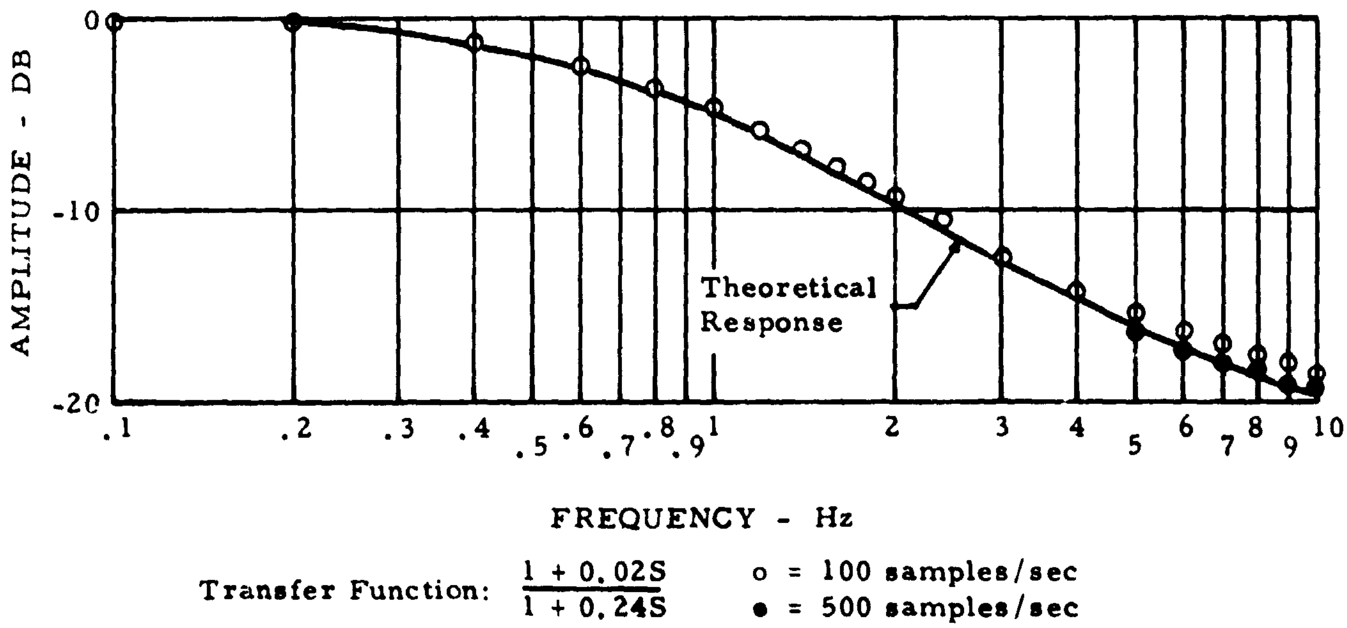
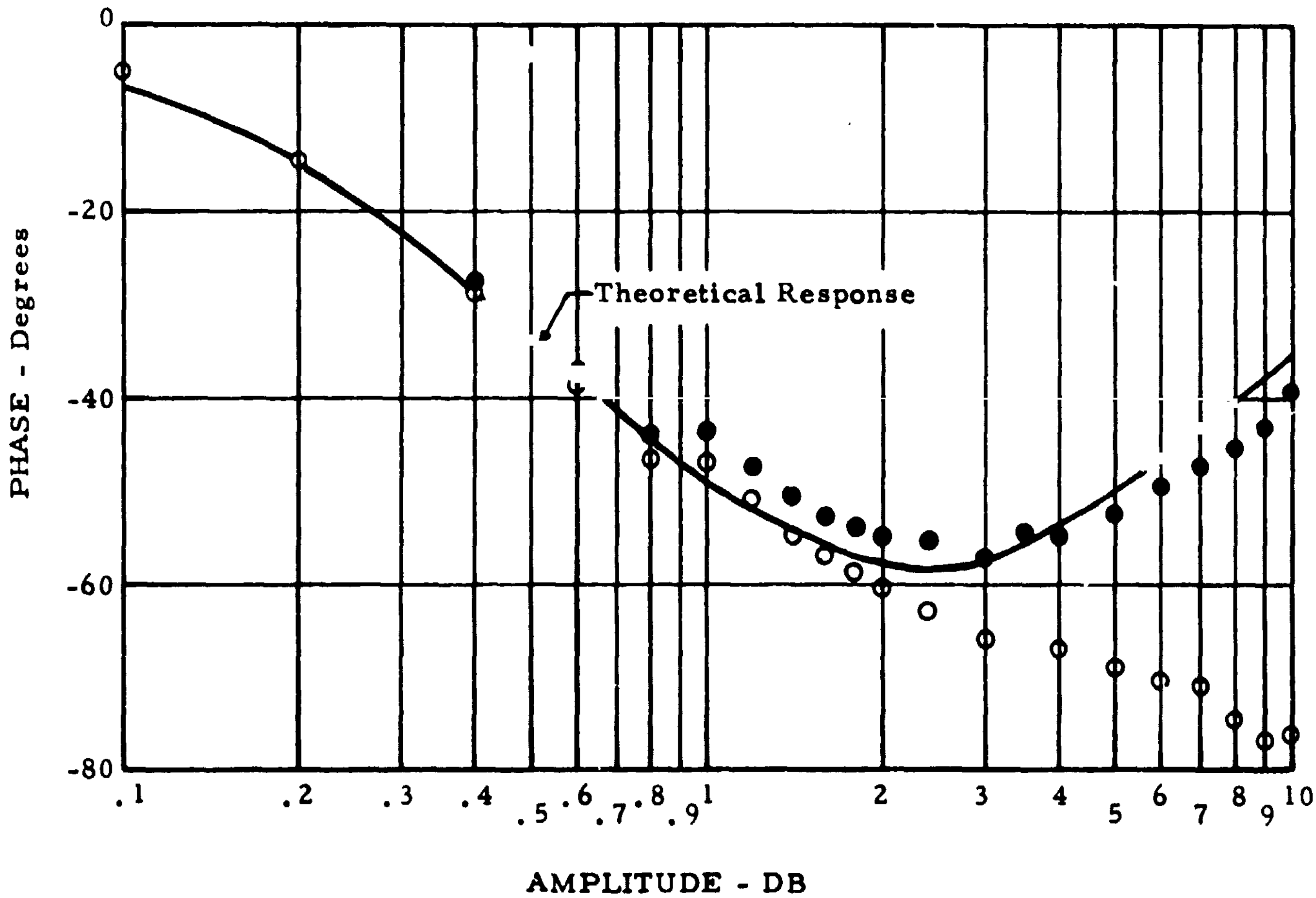


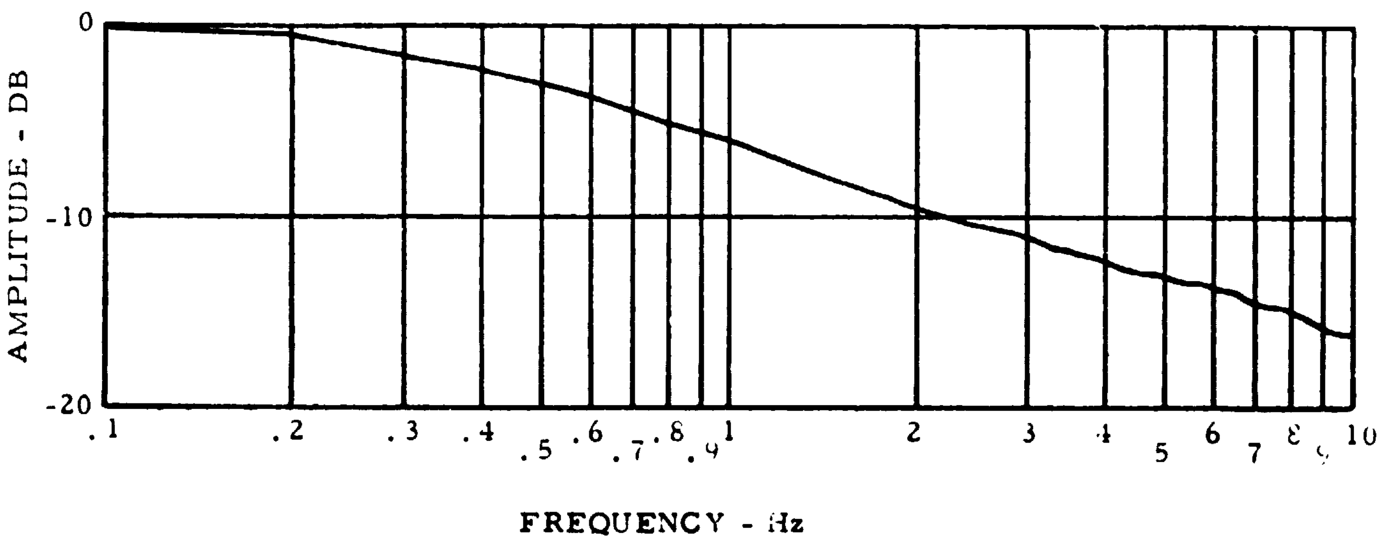
Figure 4-8. Plot of Amplitude vs Frequency for Forward Door Loop Lag-Lead Network Comparing Digital Mechanization of Two Sampling Rates with Respect to the Theoretical Response



Transfer Function: $\dfrac{1.0 + 0.02S}{1.0 + 0.24S}$

o = 100 samples/sec
• = 500 samples/sec

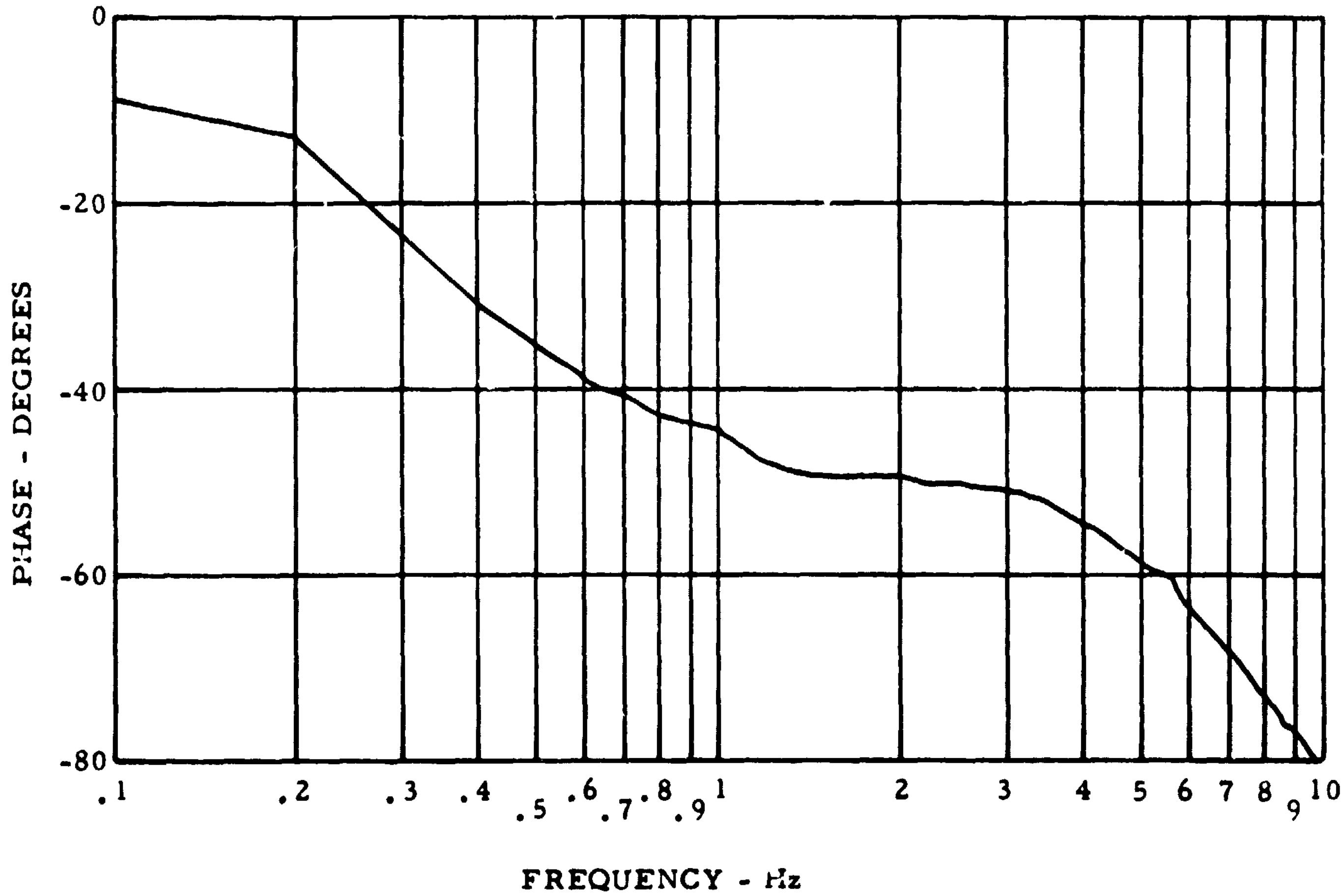
Figure 4-9. Plot of Amplitude vs Phase for Forward Door Loop Lag-Lead Network Comparing Digital Mechanization of Two Sampling Rates with Respect to the Theoretical Response



Transfer Function: $\left(\frac{1.0 + 0.08S}{1.0 + 0.32S}\right)\left(\frac{1.0 + 0.007S}{1.0 + 0.021S}\right)$

NOTE: Data sample rate = 50 samples/sec

Figure 4-10. Plot of Amplitude vs Frequency for Forward Door Loop Lag-Lead Network, Final Digital Mechanization



Transfer Function: $\left(\frac{1.0 + 0.08S}{1.0 + 0.32S}\right)\left(\frac{1.0 + 0.007S}{1.0 + 0.021S}\right)$

NOTE: Data sample rate = 50 samples/sec

Figure 4-11. Plot of Phase vs Frequency for Forward Door Loop Lag-Lead Network, Final Digital Mechanization

Figures 4-6 and 4-7 represent the theoretical gain and phase responses of this transfer function. Figures 4-8 and 4-9 show the gain and phase responses of two digital mechanizations of the transfer function, one at 100 samples per second and the other at 500 samples per second. These data provided the first indication that the same transfer functions that had been mechanized in the old analog inlet computer could not be used. As is evident, the gain of the transfer function was duplicated with minimal error at 100 samples per second; whereas the phase response at 100 samples per second was not representative at all.

Figures 4-10 and 4-11 are the gain and phase responses of the network that had been implemented in the inlet forward door loop when the system was tested in flight. It is evident that there is a major difference in the phase response of this network (Figure 4-11) and the theoretical response (Figure 4-7). This network had been selected empirically (using the hybrid simulator at Rye Canyon to simulate the forward door actuator) because it provided no bypass door overshoot for step commands.

4.2.2 Gain Schedule Tests

The gain schedule tests were performed to evaluate the performance of the inlet scheduler module which calculates spike position and DPR as a function of angle of attack, angle of sideslip, Mach and normal acceleration. The inlet scheduler module also handles the manual inlet controls, inlet unstarts, and spike and DPR calibration offsets. This effort was described in greater detail in connection with the inlet control system discussion in Appendix A, Paragraph V. The results of the tests are presented in Appendix A, Figures A-15 thru A-20, which contain plots of spike position versus Mach as a function of angle of attack; spike position versus sideslip angle as a function of Mach; and DPR versus angle of attack and sideslip angle, both as functions of Mach.

4.3 CLOSED LOOP TESTS

4.3.1 Aircraft Simulation for Closed Loop Tests

Prior to flight testing, simulations of the YF-12C aircraft aerodynamics and propulsion system constituted the primary tool for testing and evaluating the CAPCS hardware and software. All sensor and actuator dynamics were included in these simulations because there was no iron bird simulator available to reproduce these functions with aircraft hardware.

The aircraft simulation used in support of the CAPCS program was derived from an earlier simulation described in Reference 2. The original simulation was a small perturbation model of the YF-12 aircraft about a Mach 3 cruise flight condition. It was used to support work on an improved altitude hold and speed hold autopilot for that aircraft. Over a period of time the model was expanded to include the effects of freestream temperature variations on the propulsion system, the effects of Mach number and angle of attack on the aircraft aerodynamics, and a revised engine thrust calculation that better matched flight test data.

When the CAPCS program was conceived and it was decided that the YF-12C aircraft would be used for the program, the simulation was revised again. Rather than use the linearized aerodynamics from the old simulation, the full force and moment equations from Reference 3 were programmed on an EAI 8400 Digital Computer so that a wider range of flight conditions could be accurately modeled. The inlet portion of the propulsion system model was also changed to a nonlinear simulation which more accurately represented the aircraft inlet (References 4, 5 and 6). The inlet duct, spike actuators, and forward bypass door actuators were modeled on an analog computer so that the dynamics of these systems would be properly simulated. The resulting YF-12C simulation was found to be accurate over the following range of flight conditions:

Mach Number:	2.5 to 3.0+
Altitude:	50,000 ft. and above
KEAS:	250 to 450

Several aircraft systems, the air data computer, the autopilot, the inlet control system, and the autothrottle system, were also programmed in the simulation. These systems could be switched in or out so that CAPCS control results could be compared directly with the outputs generated by these independently simulated systems. A simplified block diagram of the simulation with CAPCS control is shown in Figure 4-12. The computers used to simulate the various systems are also indicated as well as some of the input/output parameters.

When the CAPCS was being operated in conjunction with the aircraft simulation, there was a continual exchange of parametric information. The parameters that were involved are listed in Table 4-1. A Brush analog recorder was used to monitor all parameters of interest in real time on strip charts.

4.3.2 Closed Loop Test Results

The primary method of verifying the CAPCS dynamic response was to operate it closed loop in conjunction with the aircraft simulation. Two of the benefits of this method were that input variables could be considered independently and each CAPCS subsystem could be operated separately. It was also possible to test the total CAPCS so that proper program sequencing was assured. Greatest stress and emphasis were given to the pitch autopilot and the inlet control system in the closed loop tests. This was because the pitch autopilo involved a large number of submodes and the inlet control system had high frequency response requirements.

Since the goal of phase I of this program was to reproduce as precisely as possible the analog systems that were replaced by the CAPCS, direct comparisons to simulated analog systems were used as a standard of performance. These comparisons were achieved by programming the CAPCS functions on large-scale fixed base computers where sample rates and cycle times allowed good analog reproduction. The aircraft simulation was operated

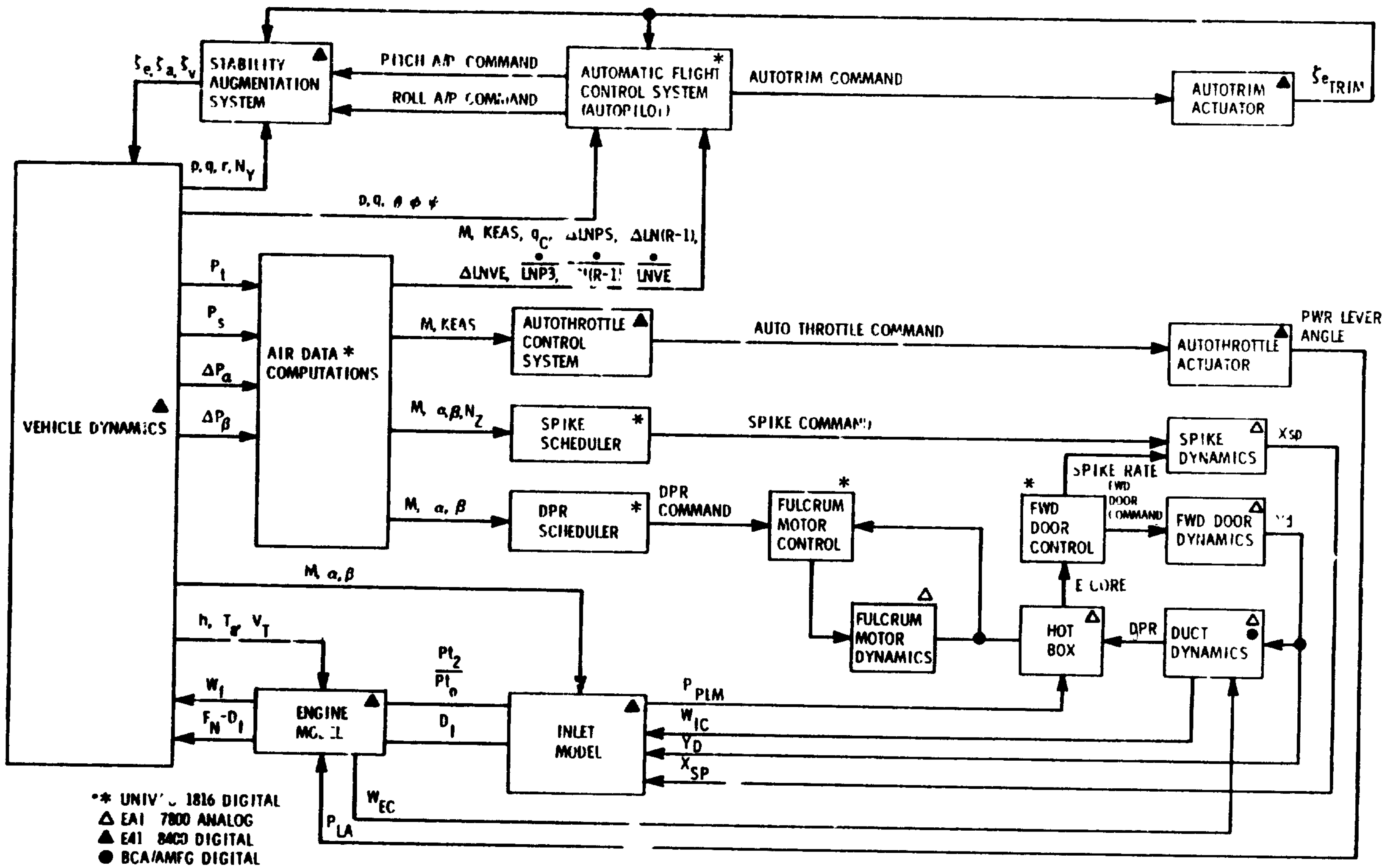


Figure 4-12. CAPCS - Controlled Aircraft Simulation, Simplified Block Diagram

TABLE 4-1. PARAMETRIC OUTPUTS TO AND FROM CAPCS AND AIRCRAFT SIMULATION

Simulation Outputs to CAPCS	CAPCS Outputs to Simulation
Roll Rate	Left Elevon Servo Amplifier
Pitch Rate	Right Elevon Servo Amplifier
Yaw Rate	Vertical Fin Servo Amplifier
Lateral Acceleration	Pitch Trim Actuator Command
Normal Acceleration	Fulcrum Motor Drive Command
Pitch Attitude	Forward Bypass Door Valve Command
Roll Attitude	Spike Valve Command
Heading	
Elevon Trim Motor	
Nose Boom Total Pressure	
Nose Boom Static Pressure	
Angle of Attack Differential Pressure	
Angle of Sideslip Differential Pressure	
Duct Pressure Ratio	
Pressure Ratio Transducer Fulcrum Position	
E Core Output	
Spike Spool Voltage	
Spike Position	
Forward Bypass Door Position	

with both the CAPCS and the simulated analog systems in the loop. Specific tests involving simulated aircraft performance parameters were then run and the performance of the CAPCS and the analog systems were then compared. For those tests in which the CAPCS was found to have poor performance, adjustments were made in logic, sample rates and gains until a good comparison was achieved. The tests were run at a number of flight conditions from Mach 2.5 to Mach 3.0+. Tables 4-2, 4-3 and 4-4 list typical examples of the tests that were used for the evaluations.

4.3.2.1 Forward Bypass Door Response. Figure 4-13 shows simulation outputs which correspond to test runs 1 and 2 of Table 4-2. These tests were designed to check the response of the forward bypass door control system to changes in engine airflow. The magnitudes of the test inputs (ΔW_{ec}) were obtained from Reference 6. The input is a 6.9 lbs/sec per second decrease in airflow, followed by a 20.6 lbs/sec per second increase in airflow, then a 3.75 lbs/sec step increase followed by a 1.25 lbs/sec step decrease in airflow. The forward bypass control system was designed so that it could follow the airflow ramps and could respond to the 1.25 lbs/sec step without unstarting. For comparison purposes, the analog traces are shown displaced 1 second from the CAPCS traces. The inlet airflow parameter (ΔW_{ic}) is calculated for the compressor face station and responds to both ΔW_{ec} and forward bypass door position as would be expected. The duct pressure ratio (ΔDPR) indicates some differences between the CAPCS and the analog system. The DPR is significantly larger at 9 seconds for the CAPCS, indicating that the forward bypass doors were not responding as quickly under digital control. Larger DPR's are also indicated for the step inputs. The forward bypass door responses indicate that generally the CAPCS has different characteristics than the analog system. The bypass doors do not follow the ramp inputs as well under digital control and have more overshoot in response to step increases in airflow. The net thrust trace indicates that the engine responds correctly to changes in airflow. The thrust response was an important factor when total system simulations were accomplished.

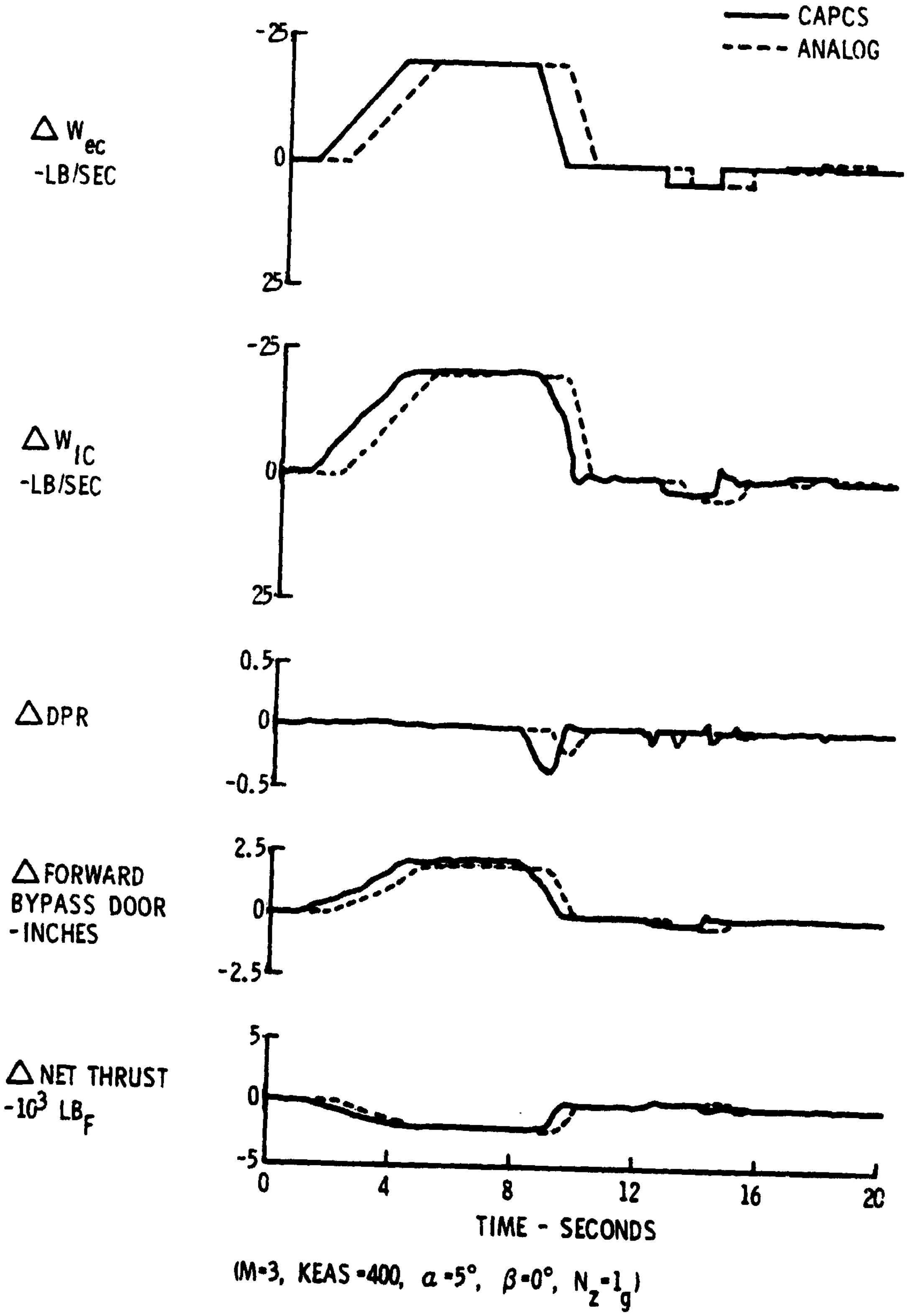


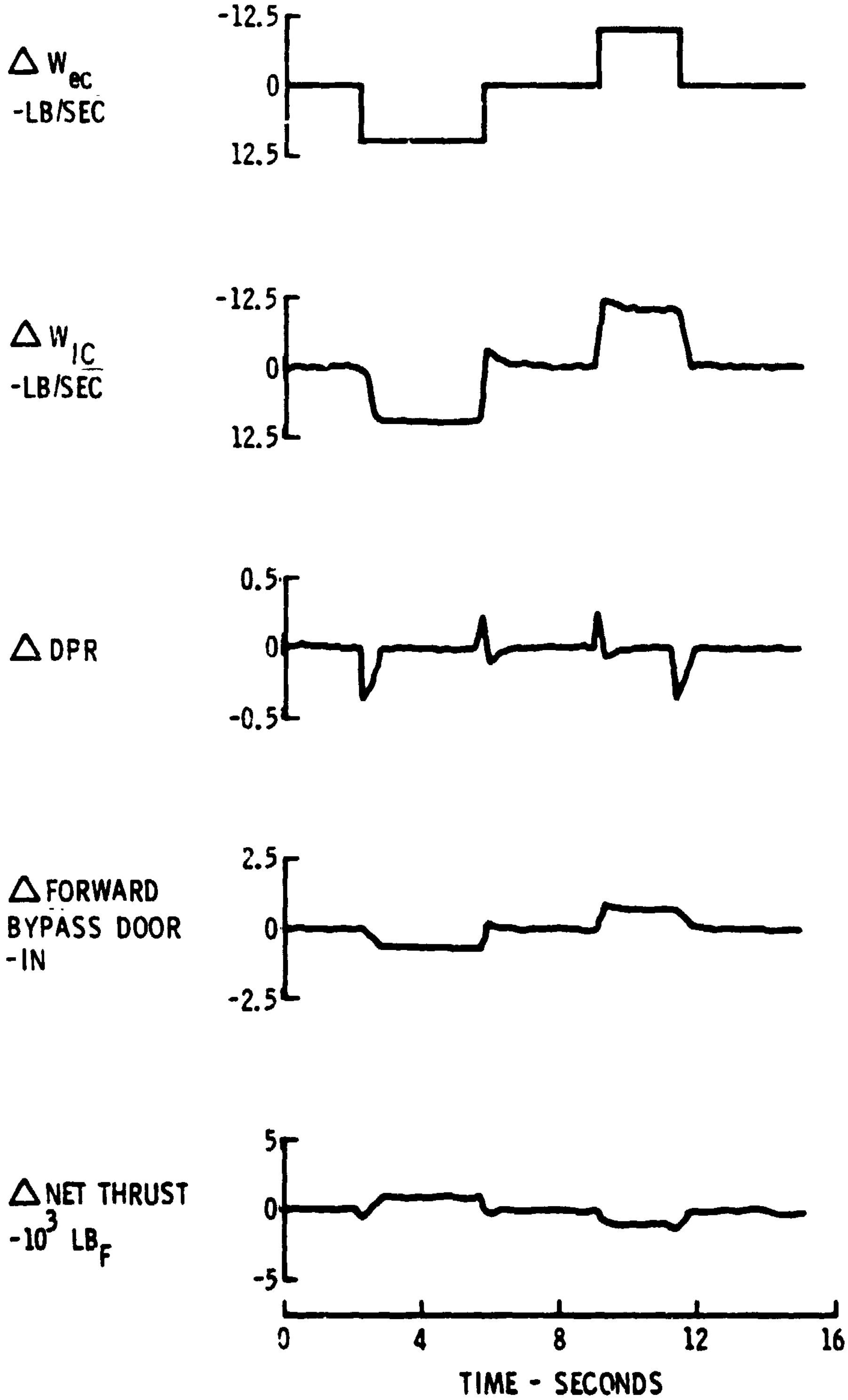
Figure 4-13. Digital to Analog Control System Comparison for Left Inlet Forward Bypass Doors

TABLE 4-2. COMPARISON OF CAPCS INLET CONTROL SYSTEM AND SIMULATED ANALOG INLET CONTROL SYSTEM PERFORMANCE IN CL.'SED LOOP TESTS WITH THE SIMULATED AIRCRAFT AT MACH 3, 400 KEAS

Test Run No.	Subsystem Type	Angle of Attack	Sideslip Angle	Normal Accel	Test Inputs
1	CAPCS	5°	0°	1g	Engine airflow ramps and small steps
2	Analog	5°	0°	1g	
3	CAPCS	5°	0°	1g	
4	Analog	5°	0°	1g	
5	CAPCS	5°	-4°	1g	
6	Analog	5°	-4°	1g	
7	CAPCS	5°	+4°	1g	
8	Analog	5°	+4°	1g	
9	CAPCS	9°	0°	1g	
10	Analog	9°	0°	1g	
11	CAPCS	1°	0°	1g	
12	Analog	1°	0°	1g	
13	CAPCS	5°	0°	0.5g	
14	Analog	5°	0°	0.5g	
15	CAPCS	5°	0°	1.5g	
16	Analog	5°	0°	1.5g	
17	CAPCS	9°	+4°	1g	
18	Analog	9°	+4°	1g	
19	CAPCS	9°	-4°	1g	
20	Analog	9°	-4°	1g	
21	CAPCS	5°	0°	1g	Large step

Figure 4-14 depicts the response of the forward bypass door control system to large step changes in engine airflow (±10 lbs/sec). This test was made to observe the time domain response characteristics of the bypass doors. The bypass door trace shows that there is no overshoot when the bypass doors are closing. This characteristic is desirable because a door closing overshoot could cause an inlet unstart. The door opening response indicates two things. First, the gaindoubling circuit, which switches in for large ΔDPR inputs, was working as indicated by the increased bypass door rate in the opening direction. Second, the doors do overshoot in the opening direction but stabilize rapidly at the proper position. Thus, based on this series of tests, the inlet control system was considered ready for flight test. It should be noted tnat no restart cycle tests were performed on the aircraft simulation because a model of an unstarted inlet was not available. The restart cycle is an open loop control system and its mechanization was considered to be rather straightforward. During flight test, however, it was found that the restart cycle did not operate as well as it did in the analog system, and due to time limitations its operation was not further refined.

4.3.2.2 Pitch Autopilot Response. Figure 4-15 is a time history of a pitch autopilot test case which corresponds to test runs 7 and 8 of Table 4-3. During the test the aircraft was allowed to establish a constant rate of climb, then switched to the Altitude Hold mode when passing through 72,500 feet altitude. Only one set of traces is shown because for this particular case the analog system and the digital system corresponded exactly. Upon sensing the altitude deviation, the autopilot elevon command signal steps to its saturation level of 2.3 degrees. It stays at this level until the altitude begins to diminish. The actual elevon position is influenced by the pitch SAS, which accounts for the rapid elevon return at time equal to 2 seconds. Then, since the autopilot is still commanding down elevator, an intermediate elevon position is held until the aircraft nears 72,500 feet. As can be seen in the altitude trace, the round-out to the correct altitude is a well-damped maneuver. The other traces show



(M=3, KEAS=400, α=5°, β=0°, N_Z=1_g)

Figure 4-14. Digital Inlet Control System Response to Step Airflow Changes in the Left Fngi·ie

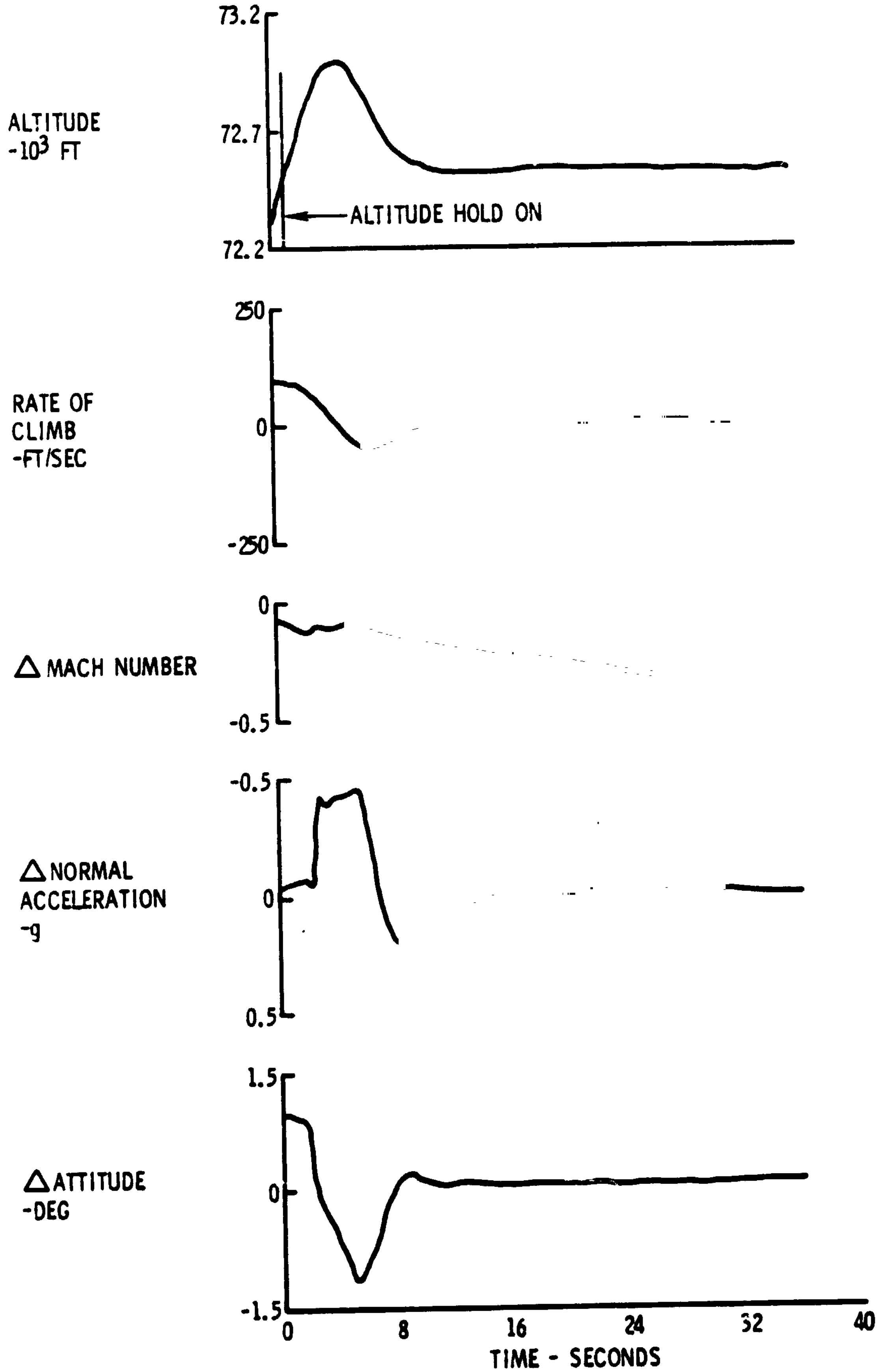


Figure 4-15. Mach 3 Altitude Hold Test Case (Sheet 1 of 2)

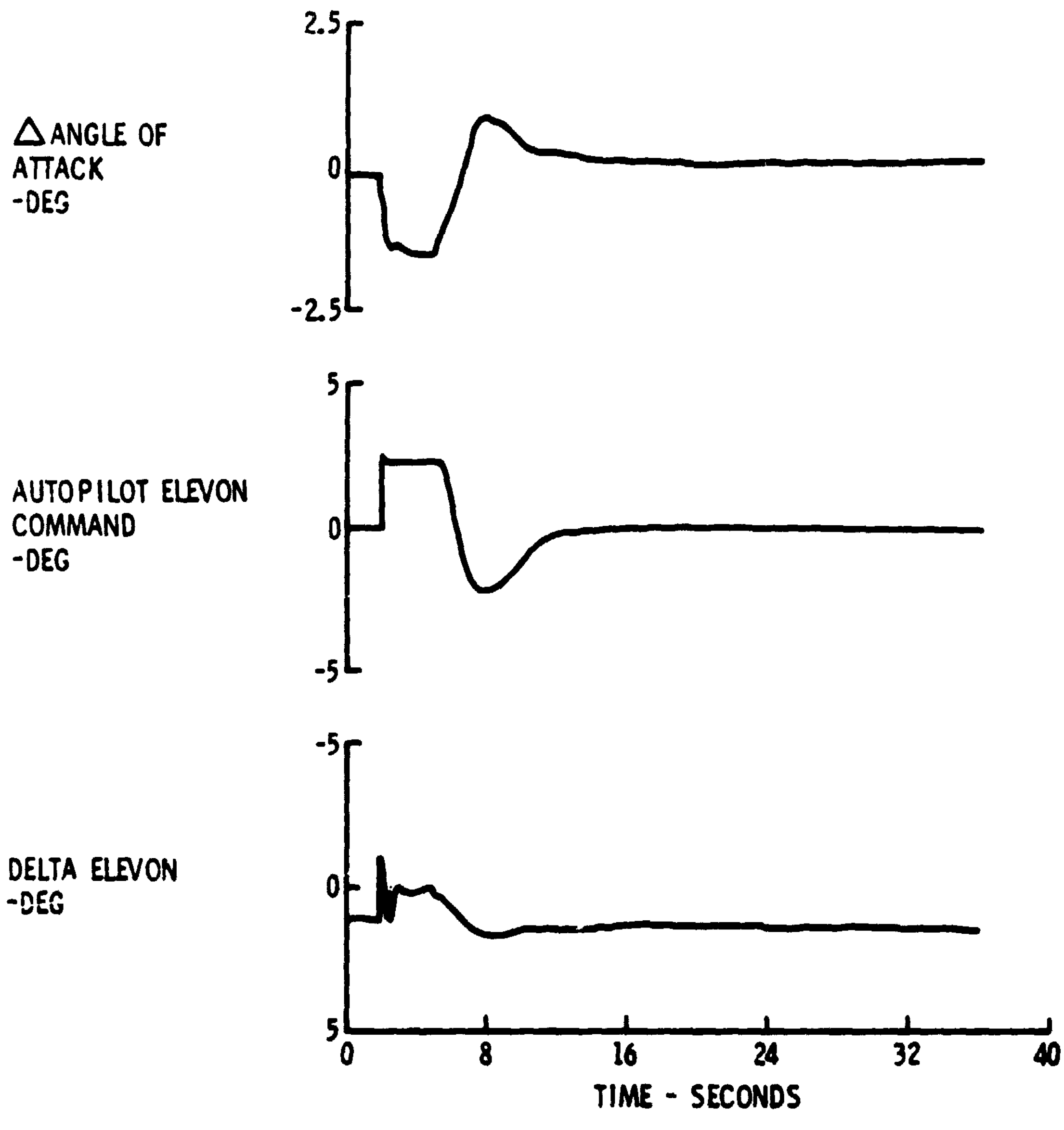


Figure 4-15. Mach 3 Altitude Hold Test Case (Sheet 2 of 2)

TABLE 4-3. COMPARISON OF CAPCS PITCH AUTOPILOT AND SIMULATED ANALOG PITCH AUTOPILOT PERFORMANCES IN CLOSED LOOP TESTS WITH AIRCRAFT SIMULATION AT MACH 3, 400 KEAS

Test Run No.	Subsystem Type	Autopilot Mode	Test Input
1	CAPCS	Attitude hold	1.5° negative pitch angle ramp followed by a 1° positive pitch angle ramp
2	Analog		
3	CAPCS	Mach hold	0.5 Mach number loss
4	Analog		
5	CAPCS	KEAS hold	0.5 Mach number loss
6	Analog		
7	CAPCS	Altitude hold	Initial climb of 20 pt/SBC
8	Analog		

the changes in the aircraft state as the autopilot is seeking the selected altitude.

4.3.3.3 Overall System Response. Figure 4-16 shows time histories of several parameters during a sideslip maneuver. For this test the CAPCS air data, autopilot, and inlet control system were operating. Again, only single traces are shown because the analog-to-digital comparisons are exact. The test input was a rudder pulse which occurred at time equal to 10 seconds. The yaw SAS was off until 20.2 seconds when it was turned on to damp out the lateral oscillations. The sideslip trace indicates that the aircraft is unstable with the yaw SAS off and some roll coupling is also evident in the bank angle trace. The inlet control system biases the DPR and spike position commands to more conservative values during sideslip. The bias is not symmetrical; the left inlet gets more bias for right sideslip than it does for left sideslip, as can be seen in the spike and DPR command traces as well as the forward bypass door and spike position traces. Complete systems tests such as this one and others listed in Table 4-4 were used to verify that the CAPCS executive routine operated properly and that the CAPCS was capable of controlling the aircraft over a wide range of conditions.

4.3.3.4 Computer Timing. In order to ensure the integrity of the CAPCS implementation, the execution of the computer subroutines must occur within fixed time bounds. The subroutine processing times were therefore measured during the closed loop tests to determine that they met this requirement and also to determine the amount of processing time remaining for future expansion.

Table 4-5 contains nominal execution times for the CAPCS routines on the FLIGHT execution list. These times are considered representative; however, several of the routines have paths that are longer in specific situations so the times are not definitive.

The overhead was gauged by putting in a variable length list routine. The length was increased until the program timed out. Since there

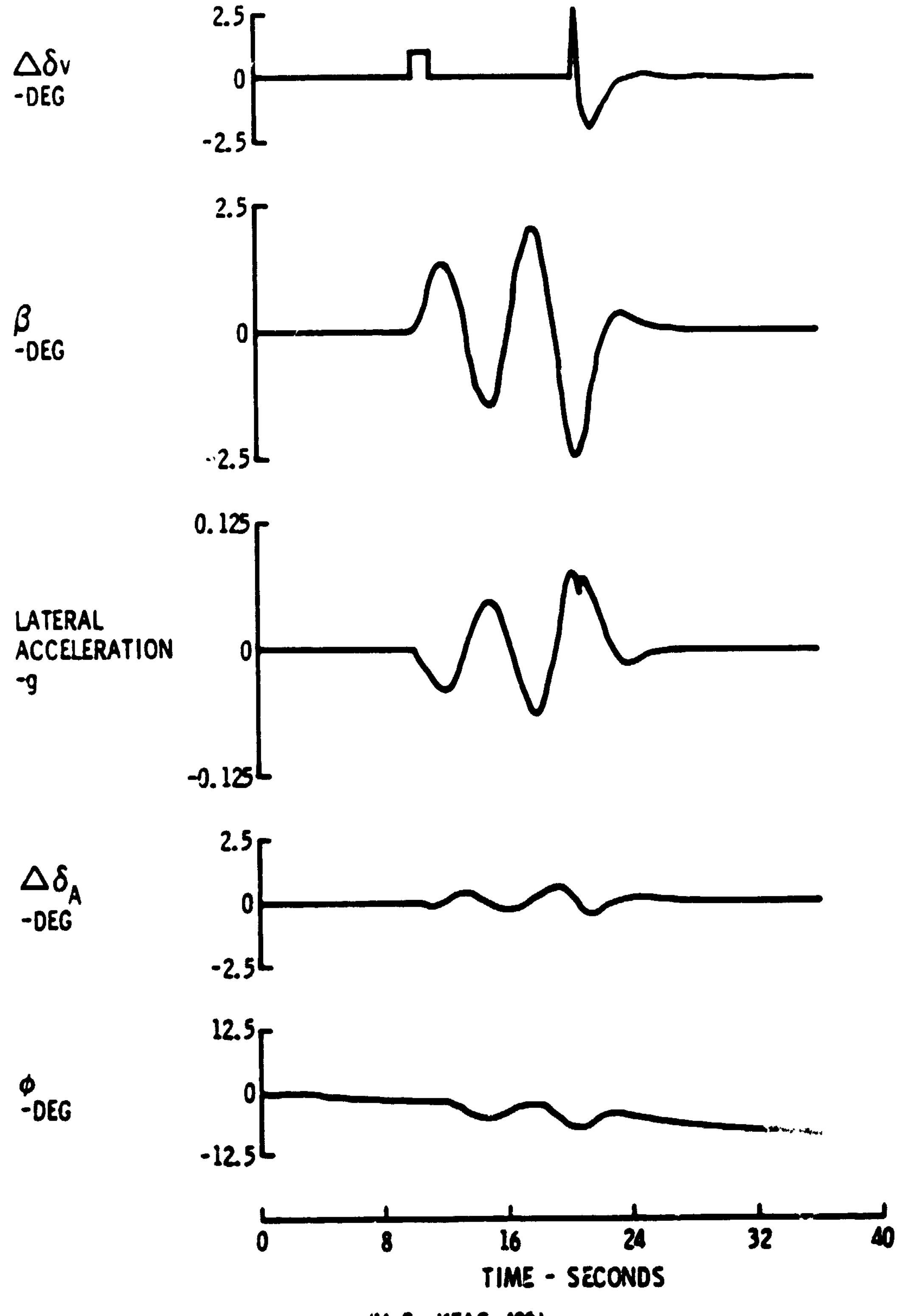


Figure 4-16. CAPCS Controlled Simulation Response to a Rudder Pulse (Sheet 1 of 2)

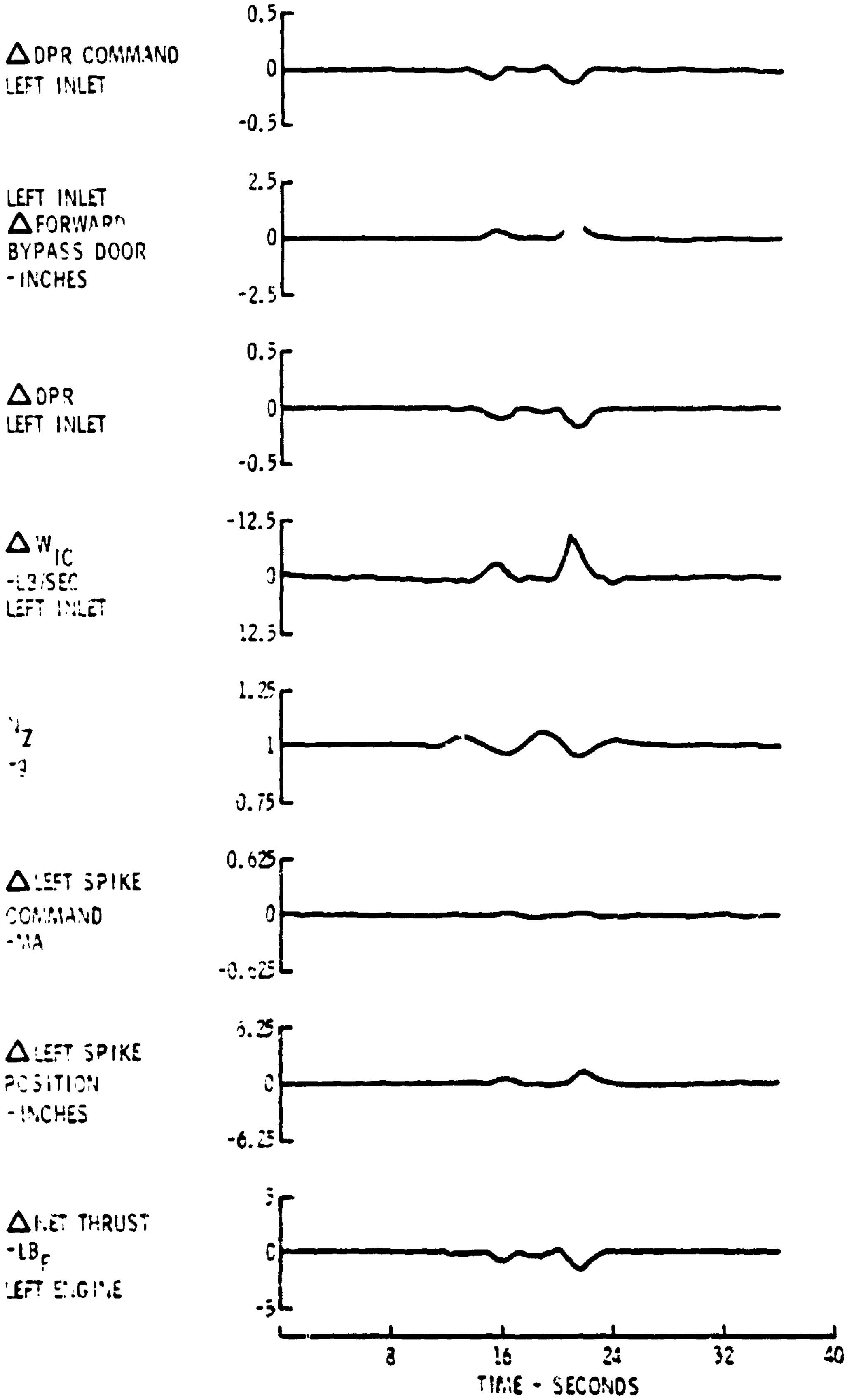


Figure 4-16. CAPCS Controlled Simulation Response to a Rudder Pulse (Sheet 2 of 2)

TABLE 4-4. OVERALL SYSTEM PERFORMANCE COMPARISON OF CAPCS AND SIMULATED ANALOG COUNTERPART SYSTEMS IN CLOSED LOOP TESTS WITH THE AIRCRAFT SIMULATION

Test Run No.	Subsystem Type	Test
1	CAPCS	KEAS climb from Mach 2.5 to Mach 3.0+ along KEAS bleed schedule
2	Analog	
3	CAPCS	Drag pulse in AFCS Mach hold at Mach 3 and 400 KEAS
4	Anal[illegible]	
5	CAPCS	Rudder pulse with yaw SAS off at Mach 3 and 400 KEAS
6	[illegible]nalog	

TABLE 4-5. CAPCS COMPUTER SUBROUTINE EXECUTION TIMES

List	Rate (executions/sec)	Subroutine Designation	Time (Millisec)
1	100	HOTBX$	74.0
2	50	FDRLP$ LATAXN PAPS1	50.0 32.5 25.0
3	20	LATAXS ATCS PAPS3 PAPS4 DACOUT*	20.0 36.0 26.0 8.6
4	10	ADCS1 ADCS2 ADCS3 CPTCHK**	26.0 26.0 9.0
5	5	INLTS$ ADCS4 PAPS2	17.0 11.0 2.4
6	1	SWITCH WRTVAL*	0.5
7	0.1	BYTE	0.2
Totals:			
Lists:		364.2 Milliseconds	
Overhead:		60.1	
5% allowance (see text):		50.0	
		474.3 Milliseconds	

* not executed during flight

** too small to measure

C-2

were inconsistencies in the measurement that were not completely resolved, the execution times listed in Table 4-6 were maximized for the sake of conservatism. In addition, 5 percent was added to account for the PCM and COCKPIT timings and to account for some of the variations in execution times. Taken together, a nominal estimate of the CAPCS processing time is approximately 47 percent or 470 milliseconds out of every second. Thus approximately 53 percent of the processing time is available for future expansion.

4.4 PREFLIGHT TESTS

The preflight tests consisted of an initial installation checkout to verify the integrity of the CAPCS installation in the YF-12C aircraft and a preflight checkout procedure to ensure that the CAPCS and all associated systems were operating correctly and compatibly.

4.4.1 CAPCS Installation Checkout

Checkout of the CAPCS installation was accomplished in three phases: power tests, electrical compatibility tests, and performance tests. Power tests were performed even though the aircraft wiring had been tested for continuity. These tests consisted of checking the availability of primary power at designated connector pins prior to installing the CAPCS on the aircraft. After installation of the CAPCS components, each input and output to the CAPCS was tested for electrical compatibility.

An interface unit test program was developed to facilitate the electrical compatibility tests. This program provided the capability of setting any output from the CAPCS to any value within the specified range of that output. It also allowed the operator to select any value for the CAPCS input parameters. The commands to the program and the results of the selected operation were inserted and printed out on the ground support equipment Terminet. Appendix H contains a general description of the interface unit test program and also contains the actual operational procedures.

TABLE 4-6. FLIGHT TEST LOG

Flight Date	Flight Number	Tests Performed	Major Anomalies
5-26-78	37-79	1. Mach 0.8, 350 KEAS, checkout of digital air data and autopilot functions 2. Standard Mach 0.8 FCF procedure 3. Mach 1.8, 400 KEAS, checkout of CAPCS, except the autothrottle system, and a manual inlet control test	1. Random total and static pressure discontinuities were noted throughout the flight
6-16-78	37-80	1. Mach 2.1, 400 KEAS, standard CAPCS tests except autothrottle 2. Mach 2.5, 400 KEAS, standard CAPCS tests except autothrottle 3. Mach 2.8, 400 KEAS, standard CAPCS tests except autothrottle	1. Random total and static pressure discontinuities were noted 2. The aircraft ride qualities were substantially degraded when in the Altitude Hold mode at Mach 2.8 3. Inlet unstarts at Mach 2.44 and Mach 2.76. Automatic restarts were accomplished 4. Data tape recorder failed prior to takeoff
7-17-78	37-81	1. None	1. At Mach 2.4 the left forward bypass door experienced sever oscillation. The door cycled at 3 Hz with a peak-to-peak amplitude of 10%

TABLE 4-6. FLIGHT TEST LOG (Continued)

Flight Date	Flight Number	Tests Performed	Major Anomalies
8- 3-78	37-82	1. None	1. Inlet unstarts occurred Mach 2.2 and automatic restarts could not be accomplished
8-18-78	37-83	1. Mach 2.75, 400 KEAS, standard CAPCS tests including autothrottle	1. Inlet unstarts occurred at Mach 2.85 and automatic restarts could not be accomplished 2. Aircraft exhibited poor ride qualities in the altitude hold mode 3. The KEAS hold autothrottle system commanded excessive throttle activity
8-31-78	37-84	1. Mach 2.8, 400 KEAS, standard CAPCS tests 2. Mach 3.0, 400 KEAS, standard CAPCS tests and FCF procedure 3. Mach 3.0, 380 KEAS, standard CAPCS tests 4. Mach 3.0+, 380 KEAS, standard CAPCS tests	1. Inlet unstart at Mach 2.8 which required a biased inlet schedule to obtain an automatic restart 2. Gain in Altitude Hold mode reduced 40% to obtain acceptable ride qualities 3. Excessive throttle activity in autothrottle modes 4. A left forward bypass door limit cycle of approximately 4 Hz and 5% amplitude was encountered at Mach 3.0+

TABLE 4-6. FLIGHT TEST LOG (Continued)

Flight Date	Flight Number	Tests Performed	Major Anomalies
9- 7-78	37-85	1. Mach 3.0, 400 KEAS, autopilot and autothrottle gain adjustments 2. Mach 3.0+, 380 KEAS, autopilot and autothrottle gain adjustments 3. Mach 2.5, 430 KEAS, autopilot and autothrottle gain adjustments 4. Mach 2.8, 410 KEAS, autopilot and autothrottle gain adjustments 5. Mach 3.0, 380 KEAS, autopilot and autothrottle gain adjustments	1. Autothrottle system operation was intermittent 2. Data tape recorder failed during the flight
9-13-78	37-86	1. None	1. Right forward bypass door oscillated from 40-90% open in both automatic and manual control settings at Mach 1.4 2. Pitch SAS B channel failed at Mach 2
9-25-78	37-87	1. Exploration of inlet unstart boundaries between 2.8 and 3.0 Mach number	1. Small amplitude forward bypass door limit cycles occurred throughout the flight

TABLE 4-6. FLIGHT TEST LOG (Continued)

Flight Date	Flight Number	Tests Performed	Major Anomalies
9-25-78	37-87	2. Mach 3.0+, 350 KEAS, standard CAPCS tests	
9-28-78	37-88	1. None	1. Right-hand forward bypass door actuator failed following an unstart at Mach 2.8 2. Data system malfunctioned, causing loss of data 3. Fire warning light went on just prior to landing
10-27-78	952-381	1. CAPCS evaluation at Mach 3.0+ by Lt. Col. Sullivan, USAF	1. Forward bypass door automatic control scheduled incorrectly, causing unstarts at Mach 2.75
12-14-78	952-382	1. CAPCS evaluation at Mach 3.0+ by Lt. Col. Sullivan, USAF	1. Navigation system failed
12-22-78	952-383	1. CAPCS evaluation at Mach 3.0+ by Lt. Col. Jewett, USAF	1. None

4.4.2 Preflight Checkout

The preflight checkout consisted of operational performance tests which served to test the interrelationships of the CAPCS and the associated aircraft systems. The basis for these performance tests were the existing preflight procedures and the 90-day checkout procedures that are currently being used to check the performance of the analog counterparts of the CAPCS. These procedures were modified slightly to meet the specific requirements of the CAPCS installation and the CAPCS unique scaling requirements. The resulting preflight procedures that were used for the CAPCS program are presented in Appendix I.

As a result of the installation checkout process, modifications to the interface unit were required. These equipment modifications were documented in the form of 129/YF Modification Orders 1 thru 34, but due to early termination of the CAPCS program they are not reflected in the "Procurement Specification, Interface Unit, CAPCS," Lab Test Report No. 199-239, Revision B. However, the Modification Orders have been provided to NASA.

4.5 FLIGHT TESTS

4.5.1 Test Concepts and Philosophy

The general objective of the CAPCS phase I flight tests was to demonstrate the operational feasibility of the digital system. This objective was accomplished. It was also hoped that the software could be brought up to production software standards in terms of storage and cycle time. This objective was not accomplished, however, due to the time limitations imposed by the foreshortened program.

Stated simply, the primary goal for the CAPCS flight test program was that the pilot should not be able to detect any difference in operation between the previous analog systems operation and the CAPCS over the full flight envelope of the aircraft. Understandably, this goal was quite subjective, However, performance comparisons based on quantitatively measured data had been made previously between the analog systems and the CAPCS using the simulator. Test inputs were closely controlled for these tests and no human reactions or observations were involved. A secondary goal of the flight test program was to assess the CAPCS reliability.

4. 2 Flight Test Plan

The first flight of the YF-12C aircraft with the CAPCS operational was on 26 May 1978. The last flight was to be accomplished before 30 September 1978, the program termination date. Due to the brevity of this test period, the flight tests were conducted in three progressive steps oriented around the established functional check flight (FCF) procedure for the aircraft as follows.

Step 1: Since the FCF procedure calls for an initial complete check of all aircraft systems at Mach 0.8 (except for the inlet system which does not begin operating until Mach 1.4.), it was planned that the air data computations and the autopilot portion of CAPCS would be checked at subsonic speeds during the first check flight. Upon completion of this test the aircraft was to be flown at a speed of Mach 1.8, during which the operation of the digital inlet control system and the manual inlet control system would be verified.

Step 2: Since the established FCF procedure calls for all aircraft systems to be checked at Mach 3.0 before proceeding to a higher Mach number, the second CAPCS test flight was planned accordingly and all operational modes of the CAPCS were to be exercised except for those involving the autothrottle. (The autothrottle control system was not scheduled to be tested until later in the flight program because it had not been fully checked out on the Rye Canyon simulator on the date scheduled for the second flight.)

Step 3: For the third flight it was planned to fly to Mach 3.0+ and back on a standard acceleration and deceleration schedule. All subsequent flights were planned to explore the flight envelope and put service time on the system.

The following system test procedures were to be used:

a. The air data computations were to be checked by employing small altitude and Mach number variations.

b. All autopilot modes were to be selected for one minute each.

c. Each of the autothrottle modes was to be exercised for two minutes while flying straight and level and for two minutes during a turn. (The turn data was necessary because throttle changes are required to hold speed when the bank angle changes at constant altitude.)

d. The inlet system operation was to be dynamically checked using $\pm$ 2 degree angle of attack and angle of sideslip variations.

4.5.3 Flight Test Results

A total of 13 test flights were flown during the course of the CAPCS program. Table 4-5 is a flight test log which lists the specific tests that were performed and any major anomalies that were noted during each flight. Flight test data were recorded in two ways: (1) real time data were transmitted from the aircraft via a telemetry link to a ground station, and (2) all of the available parameters were recorded on an onboard tape recorder. The real time data were used for flight safety purposes and also to facilitate selection of specific portions of the onboard tape recorded data that would be the most useful for postflight analysis and evaluation of CAPCS performance.

A block diagram of the YF-12C data recording system is shown in Figure 4-17. Most of the instrumentation sensor outputs are encoded by the aircraft PCM system. In addition, 16 channels of CAPCS computer data, selected by the flight crew, are also encoded by the PCM system. The resultant PCM system outputs are then recorded onboard and also telemetered to a ground station to permit real time monitoring during the flight. The primary drawback of the telemetry system was that the aircraft was out of range for approximately 20 minutes of each flight.

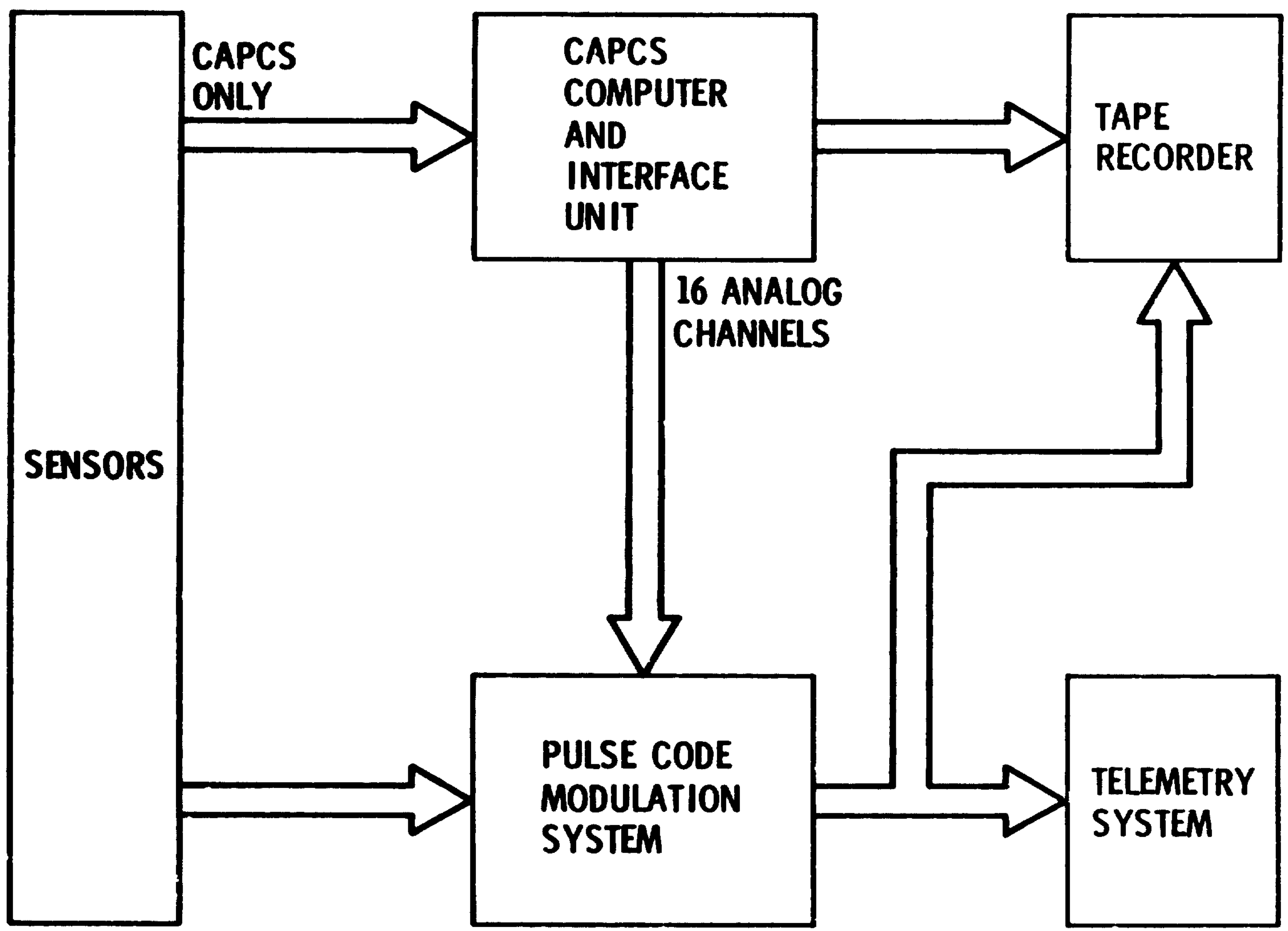


Figure 4-17. Data Recording System Aboard YF-12C Aircraft

4.5.3.1 Flight 37-79. During the first flight the CAPCS worked well. All tests planned for the flight were performed. The only problems noted were several random transients in the measurements of nose boom total and static pressure. Figure 4-18 depicts one such transient in the static pressure measurement and illustrates its effect on other variables that were computed or controlled by the CAPCS. In this case the static pressure increased while the total pressure stayed constant, yielding an apparent decrease in Mach number and altitude. The altitude rate computation, which is a derivative algorithm, is noticeably perturbed. The inlet spikes move forward as expected because of the lower computed Mach number. The forward bypass doors move in the closing direction since the DPR command is greater at Mach 1.6 than it is at Mach 1.8 for the DPR command schedule that was being used. These pressure transients were of concern because bypass door motions like those in Figure 4-18 could cause inlet unstarts at higher Mach numbers.

4.5.3.2 Flight 37-80. Between the first and second flights a full checkout of the air data transducers and their associated wiring was accomplished in hopes that the pressure transients had been caused by a bad electrical connection. Following this checkout and a complete aircraft preflight, the second flight was flown. During this flight a Mach 3 FCF and other tests at Mach numbers 2.1, 2.5, and 2.8 were scheduled. Unfortunately, the pressure transients were again experienced and several unstarts occurred at Mach 2.44 and Mach 2.76. Because of this the Mach 3 FCF was not accomplished. It was also discovered that the restart control law operated differently under CAPCS control than it did with the former analog system. Since successful automatic restarts were performed, this fact was not considered to be of immediate importance. The pitch autopilot altitude hold mode was found to hold altitude very well, but was of such high gain that an elevator oscillation was created which degraded the aircraft ride qualities. It was found after landing that the onboard data tape recorder had failed just prior to takeoff so it was impossible to make a detailed analysis of these problems.

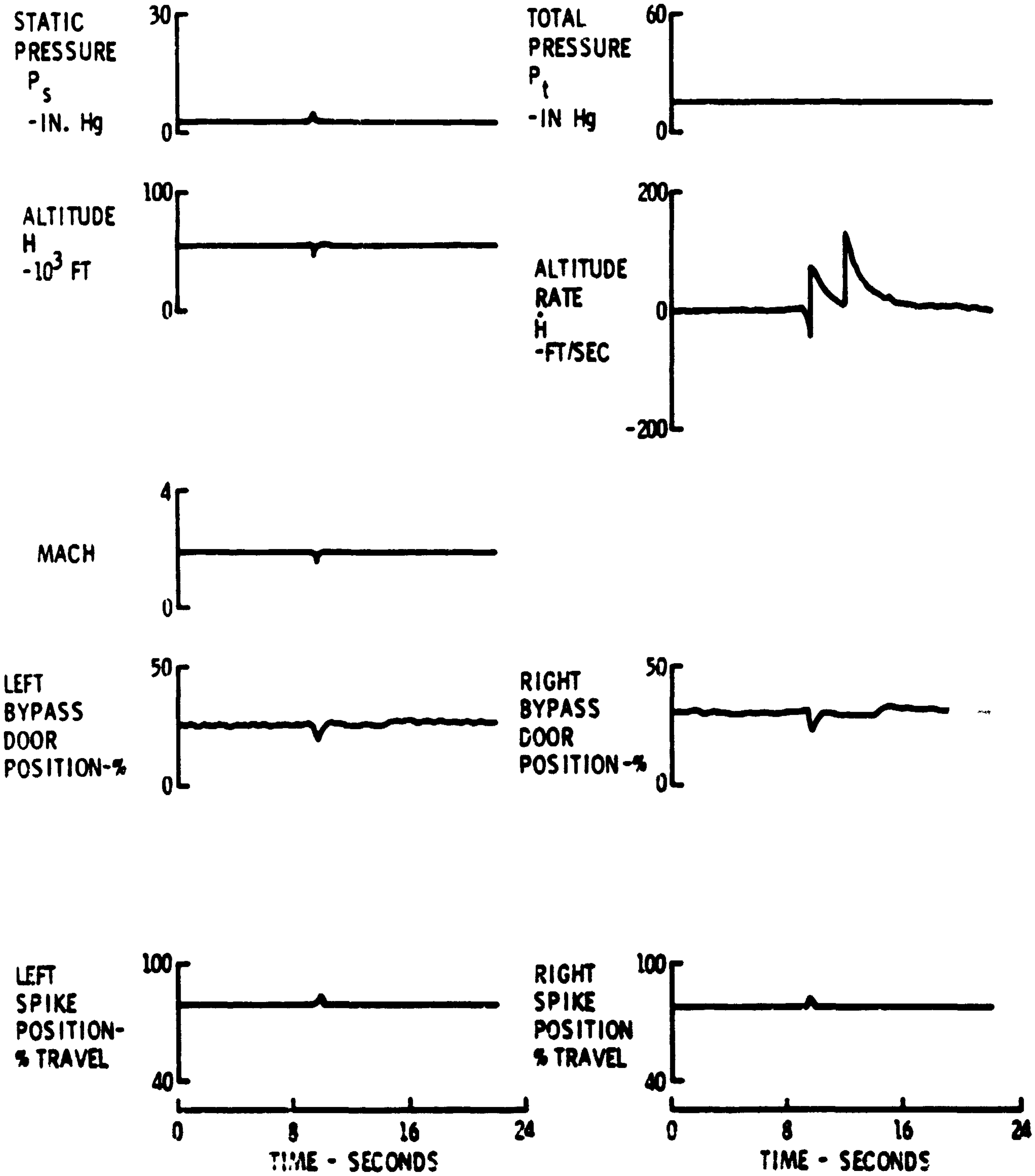


Figure 4-18. The Effect of a Static Pressure Transient on the CAPCS

4.5.3.3 Flight 37-81. Since the previously noted pressure transients had recurred during the second flight, a software change in the form of an air data filter was incorporated in the digital computer prior to this flight. This filter was actually a special routine which computed the rate of change of the pressure inputs and held the last good value if the slope was too large. Details of this computer routine were given previously in Paragraph 3.1.3. The air data filter proved to be effective in removing the random pressure transients on subsequent flights.

The tests scheduled for flight 37-81 were not completed because a major problem developed. At Mach 2.4 the left forward bypass door began cycling at 3 Hz with a peak-to-peak amplitude of 10 percent. The left inlet was placed in manual control and the flight was aborted. Postflight analysis indicated that the problem was not CAPCS related and was caused by a defective pressure ratio transducer associated with the left duct. This transducer was replaced prior to the next flight.

4.5.3.4 Flight 37-82. Figure 4-19 contains plots which depict several unstarts that occurred on flight 37-82 at Mach 2.2. The unstarts were caused by the rapid closure of the right forward bypass door after 4.4 seconds as indicated in the figure. The inlet went through one restart cycle and immediately unstarted again. After the second restart cycle the inlet remained started even though the right bypass door overshot by approximately 6 percent in the closed direction. At the 36-second point in the figure, another right forward bypass door closing transient caused a third unstart, at which point the inlets were placed in the manual mode of operation and the flight was aborted. The inlet spikes were held at the full forward position for a period of time because the digital restart control law commands the spikes to move forward at maximum rate for 3.75 seconds before beginning to retract.

4.5.3.5 Flight 37-83. Between flights 37-82 and 37-83 an extensive checkout of the inlet system was performed, but the reason for the right forward

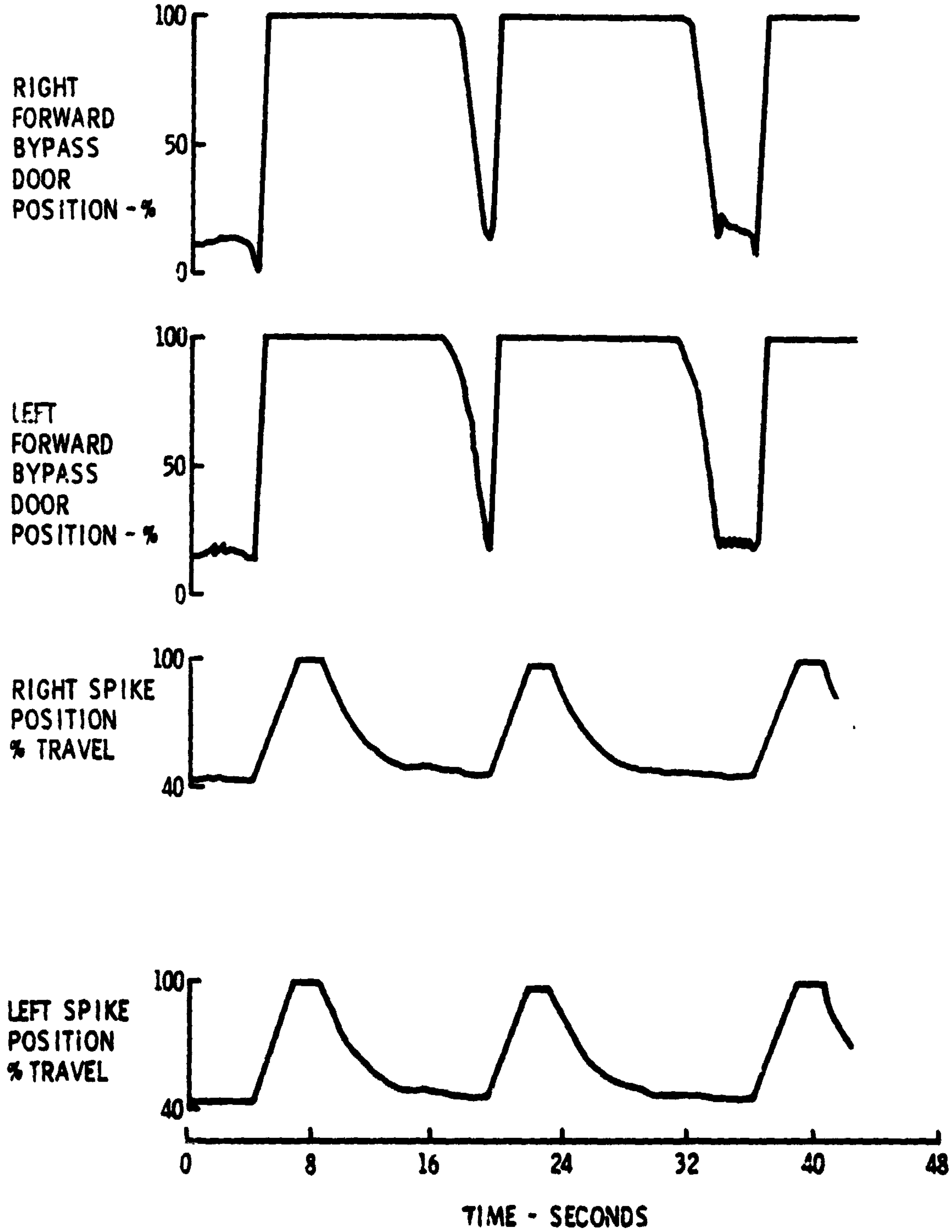


Figure 4-19. Automatic Restart Cycles at Mach 2.2

bypass closing with no command was not discovered. The restart cycle logic was also checked to see why the bypass door easy let down feature was not working. The easy let down feature was supposed to decrease the rate of door closure when the duct pressure ratio neared its commanded value. This particular feature was never made to work satisfactorily with the digital system due to the time limitation of the program.

Figure 4-20 shows a comparison between analog and digital restart cycles. During an analog system restart the spike drives full forward and immediately returns to its scheduled position. The forward bypass doors go full open, hold for 7.5 seconds, then close. When they near their scheduled position the easy let down feature decreases the closing rate. During a digital restart, the spike drives forward 58% of full travel, waits until 4 seconds have elapsed from the restart command, then returns to its scheduled position. The bypass doors go full open, hold until the spike is at its scheduled position, then close rapidly with some overshoot. It should be noted that this comparison was not made at the same Mach number. Thus the spike position scheduled by the analog and digital systems prior to the unstart and after the unstart are not the same. This digital mechanization, even though not correct, was considered good enough to allow the flight test program to continue.

Flight 37-83 was the first flight flown with the CAPCS autothrottle system working. The acceleration and climb were uneventful until Mach 2.85 was reached. At this point an inlet unstart occurred and the inlet could not be automatically restarted until the Mach number was reduced. These Mach 2.85 unstarts were of a different nature than those experienced at Mach 2.2 in that they had no apparent cause. Even though a standard DPR schedule was used, it appeared that the scheduled DPR's were too high for that particular flight condition. Since the pneumatic line lengths had been changed in the air data system and the frequency response of the inlet control system was different, it was not surprising that the analog and digital system did not operate in precisely the same manner. The rest of the flight was utilized to check the autothrottle

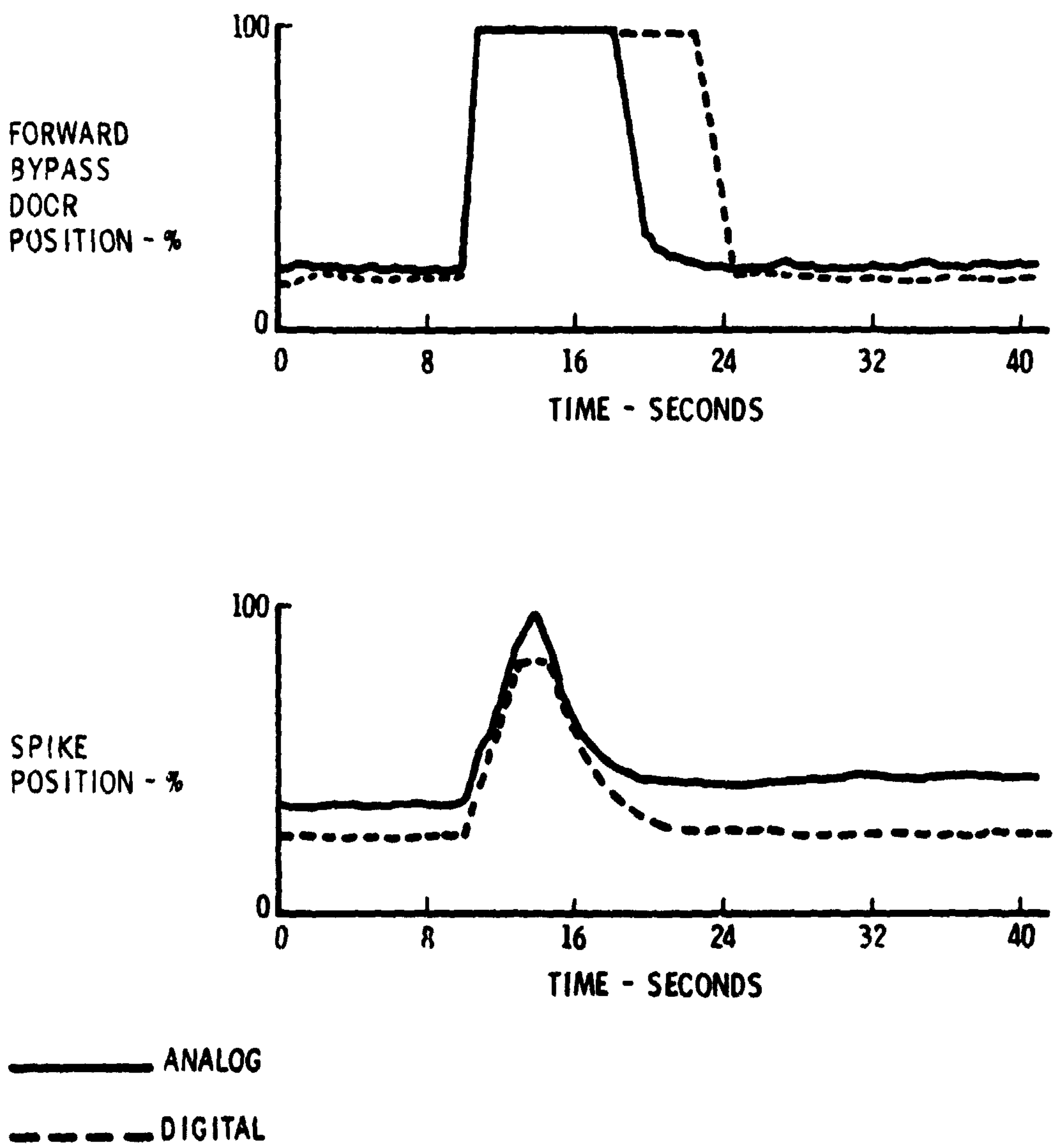


Figure 4-20. Comparison of Analog and Digital Restart Cycles

and altitude hold systems at Mach 2.75. It was found that the system gains were too large, resulting in excessive throttle activity and poor ride qualities even though speed and altitude were held very accurately.

4.5.3.6 Unstart Problem. To provide a solution to the Mach 2.85 unstart and to allow system gain adjustments to be made during flight, the CAPCS computer was programmed to allow inputs from the operators control panel located in the rear cockpit of the aircraft. This panel, which was comprised of five 10-position rotary switches, had originally been designed for the second phase of the CAPCS program. It had been planned to use the panel for selection of various subroutines which would optimize the aircraft performance over discrete portions of its flight envelope. To solve the current problems, four of the rotary switches were used to bias the inlet schedules and reduce gains in the hold modes. The function of each switch was as follows:

Switch 1: Each switch position biased the nominal spike position schedule 1/2 inch forward.

Switch 2: Each switch position biased the nominal DPR schedule -0.05 units.

Switch 3: Each switch position reduced the altitude hold system gain by 5 percent.

Switch 4: Each switch position reduced the autothrottle system gain by 5 percent.

The switches were set by the rear cockpit crew member and were engaged by pushing an ENTER button in either the front or rear cockpits of the aircraft. If the pilot did not like the effect of the entry he could enter null positions for all of the switches with a special button on the control stick. This system allowed circumvention of unstarts in two ways: (1) biases could be entered into the spike and door schedules prior to entering a part of the flight regime where unstarts were known to occur, or (2) biases could be entered during the restart cycle so that the inlet returned to more conservative spike and door positions. Even though the forward bypass doors overshot when closing, the additional bias usually allowed an automatic restart to be accomplished successfully.

4.5.3.7 Remaining NASA Test Flights. The remaining NASA flights were flown to explore the inlet unstart boundaries at high speed and to determine the optimum gains for the altitude hold and autothrottle systems. Tests were performed at several Mach number and altitude points which covered the complete flight envelope of the aircraft. The biases that were found to be most acceptable were as follows:

Schedule	Bias Setting
Spike Command	4% of full travel forward between Mach numbers 2.75 and 3.0. Nominal settings at other flight conditions.
Duct Pressure Ratio Command	-0.05 units between Mach numbers 2.75 and 3.0. Nominal settings at other flight conditions.
Altitude Hold Gain	A 40% reduction in gain resulted in good ride qualities and accurate altitude hold capability.
Autothrottle Gain	A 20% reduction in gain resulted in good speed hold capability with acceptable throttle activity.

Small amplitude forward bypass door limit cycles proved to be a continuing problem throughout the flight tests. These phenomena were not considered unusual because the analog system had exhibited the same limit cycles at certain Mach numbers. However, during the last flight in the NASA program the right forward bypass door system failed completely. Postflight inspection revealed that the ships wiring in the nacelle had worn insulation and was shorted to ground. The left inlet wiring was also in poor condition and could be grounded if vibrated sufficiently. In retrospect, it is believed that this wiring problem could have accounted for many of the intermittent inlet problems which could not be reproduced during ground checkouts. Although this problem might have been forestalled by more rigorous inspections, such as visual inspection of the nacelle wiring, it was considered more profitable from a program point of view to fly the aircraft and wait for a hard failure than to ground it for a long period while in-depth inspections were made.

4.5.3.8 USAF Test Flights. Following the NASA flight test program the USAF requested return of YF-12C, SN 937, with the CAPCS system operational. The aircraft was flown three times by USAF flight crews for operational evaluation purposes. For these flights, the computer was reprogrammed with the revised inlet schedule and the revised gains determined during the NASA flight test program.

With one exception during flight 952-381, the CAPCS functioned perfectly during the USAF flight tests. When reprogramming the computer, the DPR schedule was biased by +0.05 DPR units instead of -0.05 DPR units between Mach 2.75 and Mach 3.0. Thus, when the aircraft reached Mach 2.75 the inlet immediately unstarted and would not restart. The pilot switched to the manual inlet control system and accelerated to Mach 3 where the automatic system again worked correctly. This problem was corrected after the flight and the next two flights had no CAPCS-related problems.

4.5.3.9 Flight Test Summary. The performance goals for the phase I program were subjective. It was intended to show that the CAPCS worked like the previous analog systems it replaced and that the system was reliable. In summary, it can be stated that the system worked as expected with some minor deviations which could have been corrected during a full development program. The reliability of the CAPCS was demonstrated since no failures directly attributable to the new digital portions of the systems occurred. The system was flown for approximately 23 hours in 13 flights.

SECTION 5
CONCLUSIONS

The CAPCS was a digital control system developed on an experimental basis to demonstrate the feasibility of replacing the analog air data system, the analog autopilots, the analog automatic inlet control system and the analog autothrottle system on the YF-12C aircraft with a digital computer that was capable of performing the same computations as its analog counterparts.

During the software development phase of the program it was decided to split the subsystem functions into modules on the basis of their usage and their dominant time response. Each module was executed at a rate determined by the frequency response requirements of the particular subsystem. This type of segmentation and multiple rate computation was found to be very beneficial for software program modification, control and timing.

During the development phase of the program a large-scale mathematical simulation of the aircraft was used for integration testing and software checkout. The interface between the CAPCS and the simulation was made to represent the interface between the CAPCS and the aircraft as closely as possible. This integration and checkout procedure resulted in a relatively problem-free installation of the CAPCS equipment on the aircraft. In fact, the signal noise levels were smaller at the aircraft interface than at the simulation interface. Thus, for this system, the aircraft simulation made an "iron bird" simulation unnecessary.

When programming the subsystem analog transfer functions, the Tustin transformation method was used. This method was found to yield good amplitude reproduction of the analog transfer functions at sample rates approximately 10 times greater than the frequency response capability of the subsystems. Unfortunately, the Tustin transformation method required sample rates approximately 50 times greater than the frequency response capability of the subsystem to yield good reproduction of the phase lag characteristics of the analog transfer functions. The high sample rate required by this method rendered it unusable for digitally mechanizing the forward bypass door control loop. For that application a number of synchro-to-digital conversions had to be performed. It was found that Scott-T transformers, which yielded signals proportional to the sine and cosine of the shaft angle, were more reliable than commercially available synchro-to-digital converters. This technique required additional processing to produce the angle value, but the availability of computer hardware trignometric routines made the conversion times insignificant.

In the original system design the interface unit converted all input signals upon computer command. The operational software in the computer initiated the conversion cycle 108 times per second and proceeded with the execution of the software modules. During the development phase it was found that this design resulted in the possibility of a 75-millisecond time delay in converting alternating current signals. Thus the frequency responses of the subsystems that had AC signals were sharply reduced. Based on this experience, the final version of the interface was redesigned to free run, and all parameters were converted at 400 times per second; this helped significantly to minimize the effect of analog-to-digital conversion on the subsystem response times.

During the flight test portion of the program only two problems of significance were discovered. The first problem was a region around 2.8 Mach number where many unstarts occurred when a standard duct pressure ratio schedule was used. The second problem was an incorrect representation of the automatic inlet restart function. This problem prohibited the inlet control system from accomplishing an automatic restart at some flight conditions. These problems could have been solved by changing the inlet control schedules and further developing the inlet restart logic based on flight test results. It is significant that in approximately 23 hours of flight there were no failures attributable to the digital system.

REFERENCES

1. Reukauf, Paul J., Burchaw, Frank W. Jr., and Holzman, Jon K., "Status of a Digital Integrated Propulsion/Flight Control System for the YF-12 Airplane," AIAA Paper No. 75-1180, September 1975.

2. Brown, Stuart C., "Computer Simulation of Aircraft Motions and Propulsion System Dynamics for the YF-12 Aircraft at Supersonic Cruise Conditions," NASA TMX-62245, August 1973.

3. Lockheed-ADP Document No. SP-508, "Handling Qualities of the SR-71," dated 29 October 1964.

4. Lockheed-ADP Document No. SP-1705, "YF-12A Dynamic Inlet Computer User's Manual," dated 23 March 1971.

5. Lockheed-ADP Document No. SP-509, "Feasibility of Backup Inlet Control," dated 6 February 1963.

6. Lockheed-ADP Document No. SP-403, "Specification for Air Inlet Control Electronics," dated 12 March 1964.

7. Sperry-Univac Specification SB-10222, "Product Function Specification, Digital Computer Set 1816, Microprogrammed-Airborne," Revision K.

8. Lockheed-ADP Document No. LTR No. 199-239, "Procurement Specification, Interface Unit, Cooperative Aircraft Propulsion Control System," Revision B, dated 1 July 1977.*

9. Livingston, S. P., and Gracey, W., "Tables of Airspeed, Altitude, and Mach Number," (based on latest international values for atmospheric properties and physical constants), NASA Report D-822, August 1961.

*** Equipment modifications were documented in the form of 129/YF Modification Orders 1 thru 34. These equipment modifications are not reflected in the "Procurement Specification, Interface Unit, CAPCS," Lab Test Report No. 199-239, Revision B. However, the Modification Orders have been provided to NASA.**